LESSONS LEARNED

FROM THE
VIKING PLANETARY QUARANTINE

AND

CONTAMiNATION CONTROL EXPERIENCE

for

Contract NASW-4355
NASA Headquarters
Washington, DC

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ABBREVIATIONS

Ag-Zn	Silver-zinc
BISS	Biological Isolation Suits
C14	Labeled carbon
CHSU	Collector Head Shroud Unit
COSPAR	Committee on Space Research
DNA	Deoxyribonucleic acid
DQD	Depth of discharge
ET0	Ethylene Oxide
GC	Gas chromatograph
GCMS	Gas Chromatograph Mass Spectrometer
JPL	Jet Propulsion Laboratory
LaRC	Langley Research Center
LPA	Loader Processor Assembly
MAST	Model Assembly Sterilizer for Testing
MOI	Mars-orbit-insertion
MP	Mandatory parts
MRSR	Mars Rover Sample Return
N2H2	Hydrazine
NASA	National Aeronautics and Space Administration
Ni-Cd	Nickel-cadmium
OCC	Organic Contamination Control
Pc	Probability of Contamination
PDA	Processor Distribution Assembly
Pg	Probability of Growth
PP	Planetary Protection
PQ	Planetary Quarantine
PR	Pyrolytic release
PSA	Photo Sensor Array
PTC	Proof Test Capsule
RF	Radio frequency
RTG	Radioisotape Thermoelectric Generators
SADL	Sterilization Assembly Development Laboratory
SOW	Statement of Work
T3E	Titan IIIE
TETM	Thermal Effects Test Model
USAF	United States Air Force
UV	Ultraviolet
VL-1	Viking Lander 1
VL-2	Viking Lander 2
VLBI	Viking Lander Biology Instrument
VCL	Viking Lander Capsule
VO-1	Viking Orbiter 1
VPO	Viking Project Office
WSTF	White Sands Test Facility
XRFS	X-ray Fluorescent Spectrometer

1.0 INTRODUCTION

The review of the Viking Planetary Protection (PP) and Organic Contamination Control (OCC) activities has several objectives. A major consideration is to provide the decision makers for future Mars missions with information relative to the Viking experience in these areas. This review is particularly timely now when future mars missions are being planned such as the Observer: the Global Network, Local Rover/Sample Return, High Resolution Orbiter; and Long-Range Rovers. These are the precursor missions that resulted from the ninety-day study after President Bush announced the United States' interest in man's presence in space.

Another objective is to provide information which will identify the influence of PP and OCC on any mission landed science design. Contaminating the science instruments with terrestrial biological or chemical contaminants can compromise the science objectives of the mission. Biological surveys of Mars, either in situ or from a returned sample, must be conducted in an environment which has a preselected limit of self-generated background influence in the case of Viking, the integrity of the organic and bioscience investigations required additional decontamination and sterilization criteria over those imposed by PP. Therefore, unmanned future Mars landing missions requirements should be addressed in the early phases of mission planning as to whether the PP constraint will overshadow the background “noise" limit of science instruments on the mission or vice versa.

The following specific activities were accomplished in the execution of this study/report.

Task 1 Lessons learned from the Viking Planetary Quarantine (PQ) literature for application to future candidate missions such as the Mars Rover Sample Return (MRSR) mission were reviewed, evaluated, and documented.

Task 2 Selected Viking project, engineering, and science participants were debriefed for opinions and insights into pertinent lessons learned from Viking Planetary Quarantine and contamination control experience.

Task 3 Current National Aeronautics and Space Administration (NASA) and Committee on Space Research (COSPAR) PQ requirements were reviewed, and the influence of any changes from the Viking era criteria on the overall PQ environment applicable to future Mars missions was evaluated.

Task 4 The problems, challenges, and major decision criteria related to Planetary Quarantine and Organic Contamination Control which affected the design selection for the Viking system elements and mission sequence have been enumerated. A mission sequence of events has been provided.

Task 5 The mutual interface and mission interactions of the science payload regarding lander self- contamination of the experiment/ample by terrestrial organisms and/or contaminants from the Viking experience perspective have been discussed, evaluated, and documented. The influence of the science non-contamination requirement on the mission sequence and/or design has also been described.

2.0 TASK 1 (2.1 of SOW)

This task is a review, evaluation, and documentation of lessons learned from the Viking Planetary Quarantine literature for application to future candidate missions such as the Mars Rover Sample Return ("RSR).

2.1 INTRODUCTION: PLANETARY PROTECTION/QUARANTINE RATIONALE FOR THE MARS ROVER SAMPLE RETURN MISSION

While it is important to satisfy the international desire not to contaminate Mars, it is equally important to satisfy the science investigation requirements. As in the case of the Viking biology and molecular analysis (organic chemistry) science instruments, one would not want to detect Earth organisms or contaminants carried on the MRSR vehicle or in its subsystems and instruments. If such contaminants were conveyed to a sample, as was the concern in the Viking case, they would tend to confuse the investigation and corrupt the credibility of the data obtained. Therefore, the policies and project-level implementations of NASA's planetary protection (PP)[1] program (formerly planetary quarantine) are very important issues for the planning and development of the MRSR mission.

Because biology/organic investigations are still an important consideration for the MRSR mission, the Viking PP experience would be applicable to the protection of such investigation even if the PP requirements were greatly relaxed or eliminated. Moreover, the Viking experience suggests that the screening standards imposed by the PP requirements represent a system-level standard that provides a margin of hardware integrity and spacecraft life that may be worth the effort even without PP as a driver. In any case, however, it is important to understand what PP is, how it has evolved, and how it has been--and is likely to be4mplemented.

2.1.1 COSPAR Agreement and NASA Planetary Protection Policy

The COSPAR international agreement stated that the probability of contamination by terrestrial microorganisms of a planet of biological interest shall not exceed one chance in one thousand. Implementation of this objective in the United States was through NASA Policy Directive 8020.1 CI, which authorized the imposition of PP requirements on NASA flight programs. As a result of this authorization, NASA imposed requirements on its flight projects through the document NHB 8020.12, "Planetary Quarantine Provisions for Unmanned Planetary Missions."

Each flight project within NASA is given a probability of contamination (P_c) allocation for each launch which is consistent with overall policy objectives. For Viking, the P_c for each launch was divided into three major categories: large impactables, ejecta-efflux, and lander sources. Using these basic categories, the Project performs a probabilistic analysis of all events and sources resulting n optimized allocation of P_c between categories.

[1] The term “planetary quarantine" (PQ) used at the time of the Viking program is still in popular use and may be thought of incorrectly as implying something different from planetary protection. This document will convert to the current term “planetary protection" (PP).

"Large impactables" are those sources for which impact on the planet is synonymous with contamination because of the large number of microorganisms present. The targeting process optimizes the suballocation of P_C to deflection, mid-course, and trim maneuvers so that there is a minimum effect on propulsion requirements. Although the allocation for this source is firm, the suballocations vary with such factors as launch dates and trajectories. “Ejecta-efflux" are those organisms which may impact the planet directly after being dislodged from the nonsterile surfaces of a spacecraft by dynamic events. "Lander sources" are those organisms which survive terminal sterilization or recontaminate a lander to form nonsterile sources.

2.1.2 Significance of Planetary Protection for Viking

To satisfy the international agreement as well as NASA's PP policy, all launch vehicle and spacecraft hardware injected into a Mars flight trajectory are considered to be possible sources of contamination for Mars. For Viking, the microbial load on the Mars orbiters, the Centaur, and the payload shroud was limited by control of the assembly environment, cleaning with appropriate fluids/solvents, and various constraints imposed on flight trajectories (cg., aim point bias); and Mars orbital altitudes afforded additional assurances that Mars would not be contaminated by these non- landing/impacting elements.

Heat sterilization of the entire Viking Lander Capsule (VLC) was required to prevent the transportation of Earth organisms to the martian surface where they could contaminate the planet or produce false results in the life-detection experiments. However, a further, more severe constraint was imposed on the Viking Project by the science requirement to preclude contamination of the Viking Lander Biology Instrument (VLBI) by terrestrial organisms, To meet this constraint, which was one chance in one million, the Viking lander was heated during terminal sterilization for durations exceeding that required for PP alone.

2.2 VIKING PROJECT PLANETARY PROTECTION

2.2.1 Spacecraft and Mission Profile

The Viking spacecraft systems are illustrated in the exploded view shown in Figure 2.1. The orbiter and lander descent capsule remained attached during interplanetary cruise and during orbital reconnaissance at the planet. During the cruise, the orbiter supplied electrical power, attitude control, and propulsion for mid-course corrections and Mars orbit insertion. Reconnaissance of the landing sites was accomplished by the orbiter prior to separation of the entry/descent capsule. After capsule separation, the orbiter relayed data from the lander to Earth and performed its own scientific investigations and data transmission.

The bioshield cap and base, which were made of Kapton, a flexible, fabric-like material, provided a biological barrier to protect the lander capsule from contamination by Earth organisms. A positive pressure was maintained within the bioshield during and following terminal sterilization to prevent re-contamination, and the pressure was then vented through a biofilter during the launch ascent into Earth orbit. The bioshield cap was ejected near the beginning of the cruise phase of the mission, and the base was ejected in Mars orbit after the lander entry and descent capsule had been released for landing. The aeroshell and base cover protect the lander from heat during entry into the martian atmosphere. After passing through the entry heating phase and decelerating, the parachute was opened and the aeroshell was ejected, Release of the parachute and base cover occurred prior to terminal descent of the lander to the surface of the planet, Radar-controlled descent rockets enabled the vehicle to touch down gently.

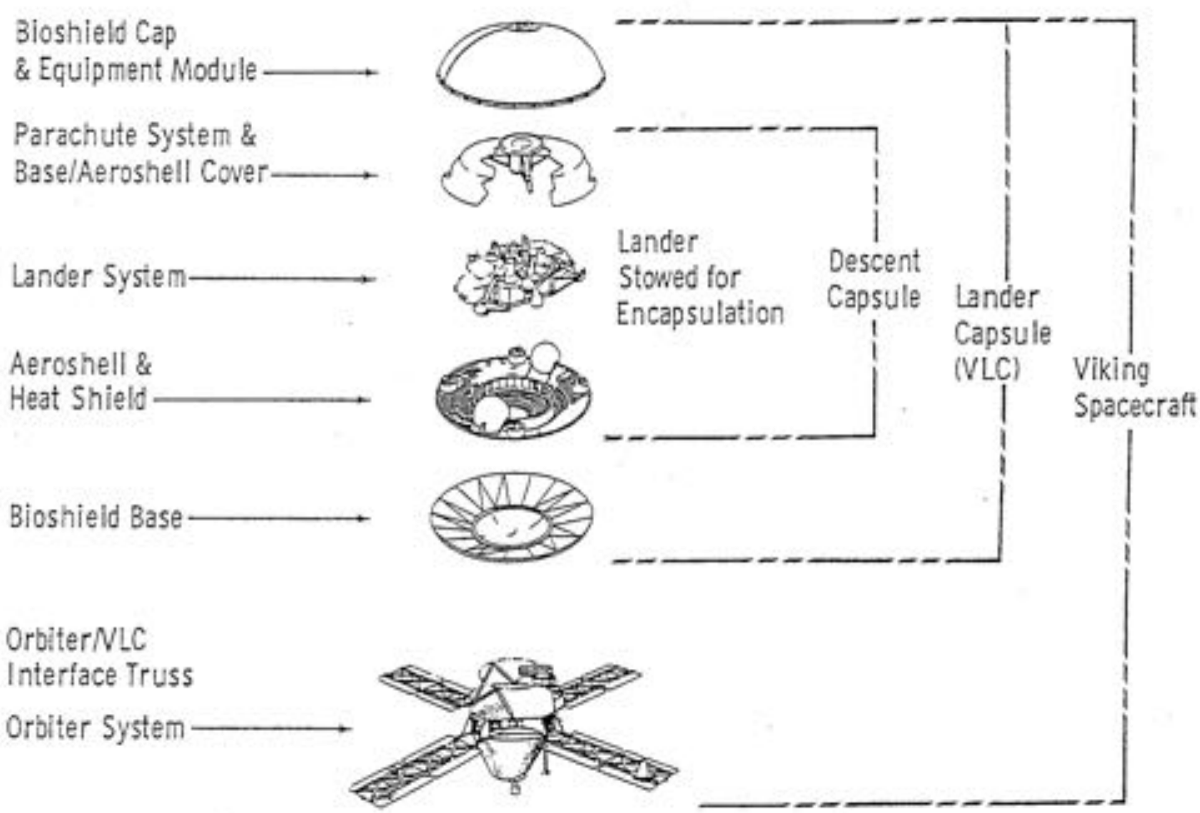

Figure 2.1 - Exploded View: Major Elements of Viking Lander Capsule

2.2.2 Planetary Protection/Contamination Control Considerations

Prior to the Viking program, considerable research was undertaken to establish that values of parameters to be used in the probability of contamination equations. This research was then reviewed by knowledgeable personnel (an advisory group), and specific values were then established for use by projects. The advisory group held alternate quarterly reviews for reporting on the status of research activities and for discussing and evaluating the research data. Personnel associated with future projects were invited to attend and participate in these reviews. This participation allowed them to become knowledgeable about acceptable practices and procedures as well as to keep abreast of the latest technology developments in the field of sterilization methodologies. Viking personnel began attending these reviews approximately two years before the Project started in 1969 and continued to participate through the launch of both spacecraft in 1975. It is felt that the early knowledge afforded by this process helped Project personnel to incorporate specific engineering requirements into the contract that ensured a highly satisfactory implementation of the PP policy.

These requirements were not only manifested as temperature requirements but also as discipline-specific requirements. There were several requirements placed on programs involving electronic parts, materials, and processes to ensure that these items would be evaluated, selected, and controlled in a manner necessary to satisfy requirements. It was recognized that the electronic circuitry associated with the accomplishment of the Viking mission would be formidable. A comparison of electronic parts between the earlier SU~VEYOI. and :he Viking Lander Capsule (VVLC) shows that the total discrete part count for Surveyor was 28,727 and for the Viking lander was 61,179. However, since Viking utilized 12,923 microcircuits, the equivalent parts count on Viking was 966,948. Equivalent parts were defined as the sum of the discrete parts plus individual resistors, capacitors, diodes, and transistors which are within the microcircuits. On the basis of discrete-part count, the Viking lander has approximately twice as many parts as Surveyor; however, when equivalent parts of microcircuits were considered, Viking has 34 times as many parts.

2.2.3 Reliability: Parts, Materials and Processes

Electronic Parts. Because of the high reliability requirements and the equivalent-part circuitry complexity specified for the VLC, a stringent parts control program was established which also accounted for the sterilization requirements, This program for the Viking lander minimized sterilization problems by first selecting a group of general-usage parts which were both ,highly reliable and inherently insensitive to dry heat up to 135C. The selection process included an internal construction analysis on all candidate parts as the step leading to a final part and source selection. The parts finally selected became the Mandatory Parts (MP) for general usage in circuit design.

The lander prime contractor procured the necessary quantity of each part as a single production lot from a single manufacturer. Inspection and screening requirements generally exceeded the then- current high reliability practices for tests such as stabilization bake and burn-in for semiconductors. The parts were qualified by testing samples drawn from flight production lots. Qualification tests demonstrated ruggedness, including 1000-hour high-temperature storage and operating stability at elevated temperatures for 2000.hours of life. These mandatory parts were then distributed to the lander component developers requiring them.

It was recognized that the mandatory parts could not accommodate the entire lander requirement, particularly the high-frequency items in RF circuitry. In addition, power and weight constraints forced miniaturizations and expanded the needs for monolithic microcircuits and complex hybrid microcircuits. These specialty items, which were classified as 'Conditional" parts, received their justification on the basis of the application. The user was responsible for part procurement and qualification, employing the same criteria applied to mandatory parts.

Because of the qualification requirement that parts withstand exposure to 135OC, the polycarbonate films, aluminum electrolytics, paper capacitors, etc. could not be used. Polysulfone film and teflon film capacitors required special screening tests to permit usage in applications where the charging current was low (e.g., timers). Applications of wet-slug tantalum capacitors were limited to exposures of 125OC to avoid yielding of the silver in the cases. The plastic tuning screws in variable capacitors had to be changed to a heat-tolerant material. Epoxy die bonding and epoxy packaging for semiconductors was unacceptable; hermetically sealed packaging was a necessity for all microcircuits, including hybrid circuits. Carbon resistors were not predictably stable within the required limits and, therefore, were not used; ultrahigh-precision resistors were mounted into hermetically sealed cases.

Mandatory parts account for 90 percent of the total lander inventory. The usage of conditional parts is the highest in the RF subsystems and those specialized applications which depend upon miniaturization. Within the RF subsystem assemblies, however, approximately 70 percent of the parts were still drawn from the MP list.

Materials. The selection qualification and control of materials used on the VLC was significant. The environments of concern were the heat encountered during sterilization and the vacuum which would subsequently be encountered in space. The effects of these environments on metals is well known and can be accounted for in design specifications. However, the effect of these environments on nonmetals is unpredictable. Therefore, the primary objective of the Viking Materials Testing Program was to determine the chemical characteristics and physical properties. of nonmetallic materials to establish data for use in subsequent component design and testing activities.

Chemical characteristics were determined by performing the following tests: thermal gravimetric analysis in vacuum and nitrogen, residual gas analysis, differential thermal analysis, isothermal weight losses in nitrogen, and collection and identification of condensibles off-gassed in vacuum. The results of these tests were used to eliminate materials which would: (1) degrade at sterilization temperatures, (2) outgas excessively, (3) outgas constituents which would degrade or deteriorate other materials, (4) interfere with the scientific experiments because of their outgassed constituents, or (5) cause malfunctions in components because of their outgassed constituents.

Materials which had acceptable chemical characteristics were subjected to physical property tests. The program had the capability to perform 29 different physical tests. These tests included such evaluations as creep, corona resistance, adhesion, thermal expansion, and sand and dust abrasion resistance, However, each material was subjected only to those tests necessary to validate its intended use.

In order to determine whether any changes occurred as a result of the environmental exposures, the tests were performed repetitively. The first series of tests were performed in air on the material 'as received.' The data obtained were considered as baseline. The same tests were performed again in air after exposure to the heat sterilization environment. Additional samples, which had been exposed to the sterilization environment, were placed in vacuum and maintained at the maximum temperatures that they would encounter during operation, At the end of one month, the tests were repeated in the thermal vacuum environment.

If the material specimens showed no evidence of degradation when compared with The baseline test data, the material was accepted. If slight degradation occurred, thermal vacuum exposure was continued. In situ evaluations were performed again at the end of three (3) months.

If unacceptable degradation of the material occurred anywhere in the testing sequence, the material was rejected. To provide additional mission assurance, the parachute materials were tested in situ periodically during 14 months of thermal vacuum storage.

Fabrication Processes. The strength of solder is considerably reduced at sterilization temperatures. Breakage or deterioration of joints could be expected where stresses exceed the relatively low strengths shown in Figure 2.2. A program was initiated to evaluate numerous solder joint configurations and to develop stress-free joints. Since the stress on the solder joint configuration is influenced by part mounting and conformal coating, the program evaluated all these areas simultaneously. It was determined the conformal coating thickness was a critical parameter in the design of stress-free joints and would require control. The solder joint configurations which were determined to be satisfactory became the basis for Viking process specifications. These process specifications, which included approved part mounting, conformal coating application, and part lead to terminal configuration, were made mandatory for all Viking electronic hardware manufacture.

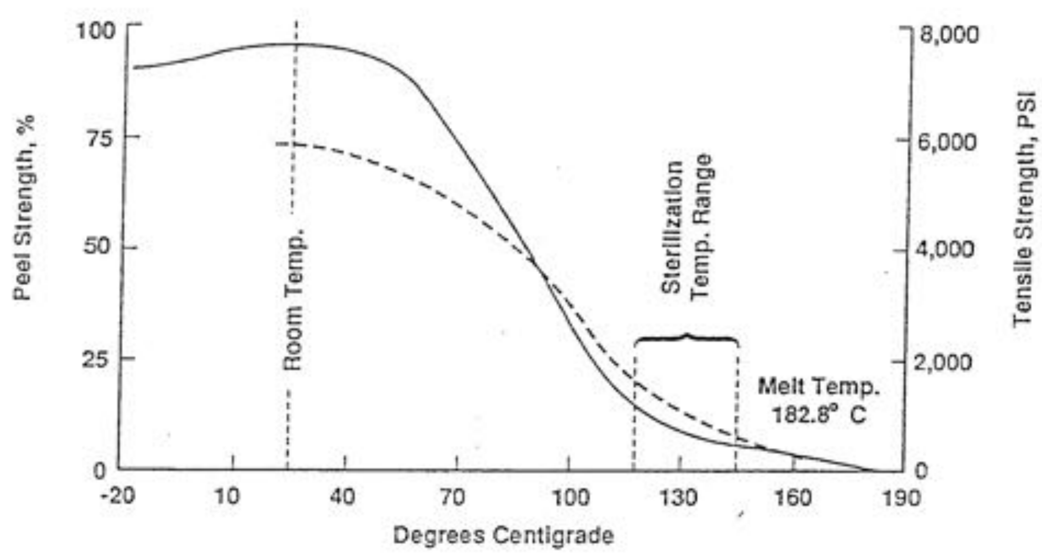

Figure 2.2 - The Strength of the Eutectic Solder Used on Viking Is Low at the Sterilization Temperatures

Packaging. The basic electronic packaging concept used was a "book-page" design, a configuration that lends itself to ease of assembly, inspection, and rework. In the final assembled unit, the printed wire boards are mounted to frames to form pages, and the pages are mounted together by use of fasteners to form a book. A problem of the reduction of fastener preload could exist if the design did not consider such factors as material thermal expansion, creep of material, and area of load distribution. Attention to design detail was required to insure that preloads were maintained during the heat process so that components and subassemblies would not be improperly attached to structural elements and possibly damaged when exposed subsequently to the launch vibration environment.

2.3 VIKING STERILIZATION: REQUIREMENTS, IMPACTS, AND PROCEDURES

The Project performed studies which considered the various techniques for satisfying the sterilization requirement. Included in these studies were the costs, engineering problems, the state Of the art of technology, and the biological assurance associated with each technique. The process selected was a dry-heat process using an inert gas. The approach taken was to achieve deep sterilization at the component or black-box level. Terminal sterilization then needed to be only sufficient to reduce the population of microorganisms accruing on the exposed surfaces during assembly and test of the VLC.

The rationale in support of this approach was that flight components are exposed to appropriate environments as a part of their engineering flight acceptance tests to determine their suitability for flight. Because of this, each component would have to experience a heat cycle, The planetary quarantine group specified the time and temperature profile for the component acceptance test in order to provide for deep sterilization where recontamination is not possible. Performing the deep sterilization at the component level minimized the terminal sterilization environment required and thus reduced the likelihood of failure, repair, and resterilization at the launch site when time was of prime concern.

This approach resulted in the hardware time and temperature requirements shown in Figure 2.3. The flight hardware was exposed to the cycle shown as component acceptance testing for deep sterilization at the component level and terminal sterilization for surface sterilization at the system level.

The ability to design and manufacture equipment capable of withstanding the requirements of the Viking heat sterilization environment has been demonstrated by the Viking program. There were relatively few component problems directly attributable to the requirement that the components withstand the sterilization environment. This was due to the attention paid to design details, to the selection and screening of electronic and mechanical parts, and to the careful selection of materials, which was emphasized throughout the program. However, the necessity to change from some common and well-understood materials and processes introduced a number of concerns.

2.3.1 Component Development

When the Viking program was initiated, there were several components which were of concern because of the sterilization requirement. Unsuccessful attempts to sterilize Ranger lunar spacecraft in the early 1960's identified many problems. The resulting research pursued during the following years pinpointed specific items which would require extensive development for Viking. With this knowledge, activities were initiated early in the Viking program to design, build, and test gyroscopes, tape recorders, and batteries which would survive the sterilization environment.

2.3.2 Gyroscope

Areas of concern due to heat cycling at the beginning of the gyroscope development program were: (1) performance variations resulting from dimensional instability, (2) outgassing and degradation of epoxy resins, and (3) mechanical integrity of the entire assembly due to pressure buildup.

Investigations involved temperature cycling of individual components and subassemblies to determine the suitability of the materials and processes used in manufacture. Tests on bearings, motor rotors and stators, full-up float assemblies, and all pressure castings showed that these times could both withstand the sterilization environment and maintain dimensional and performance stability. The only design changes required were a reduction in the rotating mass of the spin motor, a change of damping fluid, and an increase in size of the volumetric compensating bellows.

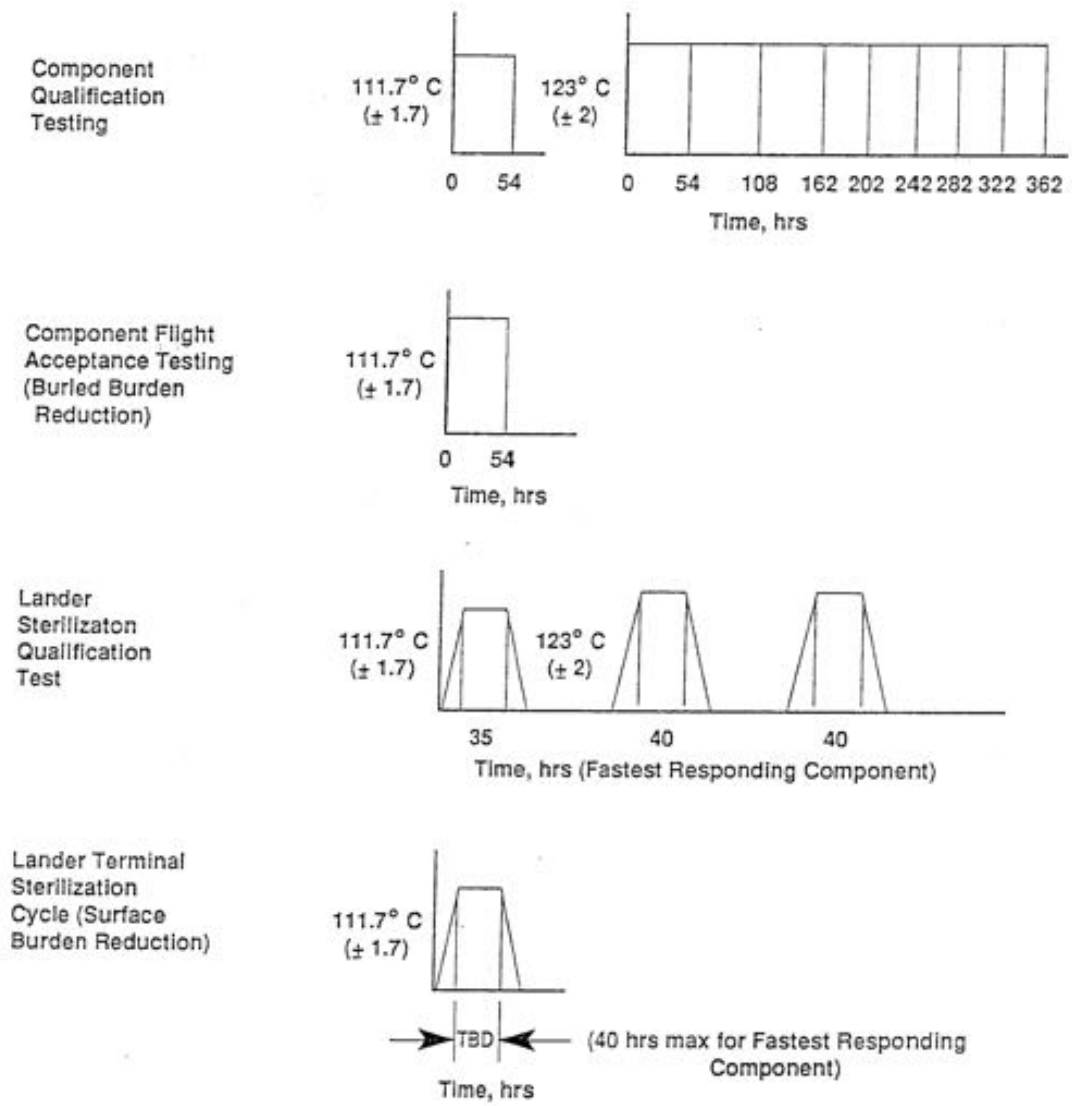

Figure 2.3 - A Graphic Illustration of the Component and System Head Cycles Used by the Viking Project

Three gyroscopes were build and tested to the Viking environmental requirement. These units demonstrated their ability to withstand the sterilization temperature, vibration, and shock environments and, subsequently, met mission performance requirements. To provide performance assurance of flight gyroscopes, the following actions were imposed: (1) a detailed subassembly dimensional inspection was performed after the thermal preconditioning heat cycle; (2) all subassemblies containing resins were treated to a maximum temperature of 135C at a pressure of 0.05 mm Hg for 48 hours to stabilize the resin systems; and (3) all gyroscopes were thermally preconditioned prior to installation in the component. Attention to design detail for heat compatibility, careful selection of materials and processes, and preconditioning of subassemblies and assemblies resulted in a Viking sterilizable gyroscope.

2.3.3 Recorder

A decision was made at the outset of the Viking Program to design a recorder specifically to meet the requirements of heat compatibility rather than to modify an existing unit. A development program was initiated to prove suitability of specific materials, processes, and components. The program tested, measured, and evaluated electronic parts, seals, lubricants, ball bearings, magnetic tape, magnetic heads, and various materials and processes. Organic materials were used only where unavoidable in the transport mechanism, and then only materials shown to have low outgassing properties were selected. Thus, the transport assembly, including -the tape, was virtually all metal. Lubrication of the tape, bearings, and gears was by a dry- lubrication process. The rotating idlers, motor housing, and capstan were fabricated from titanium to eliminate differences in coefficients of expansion.

The recorder was installed in a compartment to separate the transport mechanism from the electronics. This separation prevented Contamination of the transport mechanisms, head, and tape by outgassing from the material associated with the electronics. Prior to final assembly, individual parts were thermally preconditioned by baking at 135C in an inert gas flow to drive off entrained cleaning solvents. After final assembly, the transporter was flushed with argon gas for 12 hours at 125OC and sealed.

2.3.4 Batteries

Initially, two types of batteries, nickel-cadmium (Ni-Cd) and silver-zinc (Ag-Zn), were considered for the Viking program. Each of the battery types underwent a separate early development program. The batteries were required to be: (1) sterilizable, (2) long life (approximately 22 months), and (3) capable of surviving an 80 percent depth of discharge (DOD) during terminal descent and 50 percent DOD per day during the landed operations. The advantages and disadvantages of the Ni-Cd and Ag-Zn batteries are shown in figure 2.4. Both types of batteries were built and evaluated. However, because of continuing sealing problems with the Ag-Zn cells when exposed to the sterilizing environment and the engineering advantages that could be incurred through the use of Ni-Cd cells, the decision was made to use Ni-Cd cells and accept the associated weight penalty.

	NiCd	AgZn
Advantages	• Very long wet life (insoluble electrodes) • Thousands of cycles • Capable of rapid charging • Can take abuse • Easy to seal	• High energy density (light weight) • Low self discharge rate
Disadvantages	• Low energy density (heavy) • High self discharge rate • Requires some min charge rate	• Difficult to get long wet life • Difficult to get few hundred cycles • Has been difficult to seal • Silver and zinc shorting
Problems	• Standard separator (nylon) disintegrated	• Standard separator (Cellophane) disintegrated • Plastic cases cracked • Epoxy seals leaked
Resolution	• Polypropylene separator	• Redesign cases and seals • Polypropylene separator
Decision	• Use NiCd and accept weight penalty for advantages	

Figure 2.4 - A Comparison of the Nickel-cadmium and Silver-zinc Batteries

2.3.5 Test Vehicles and Programs

A series of test vehicles were used to provide assurance that the components, when integrated into an overall lander, would perform satisfactorily as a system in the various environments that were to be encountered on Earth, in space, and at Mars. The first was the Thermal Effects Test Mode (TETM). This was a highly instrumented mockup of the lander with each part designed to simulate the thermal characteristics and responses of the real components. One of the objectives of the TETM testing was to validate the thermal analyses that had been analytically performed and to discover any anomalies that were not accounted for in the analytical work, The TETM was instrumented with 496 thermocouples to measure the lander response to the various thermal environments to which it was exposed.

During performance of the thermal analyses it became apparent that the interior of the lander body would heat very slowly, This is a result of the insulation used on the lander body to maintain the enclosed instruments at optimal temperatures when the lander is exposed to the extremes of the martian night and day (-1 18OC to +37OC). Also, the Radioisotope Thermoelectric Generators (RTG's) had to be cooled during the heat sterilization cycle. With these two facts, a concept was implemented whereby a coil containing the heated RTG coolant was placed in the lander body to provide an interior heat source, as illustrated in Figure 2.5; thus, a more uniform temperature rise resulted throughout the lander. A sporicide was chosen as the coolant to assure that the RTG cooling lines would remain sterile throughout all launch operations after the terminal sterilization cycle.

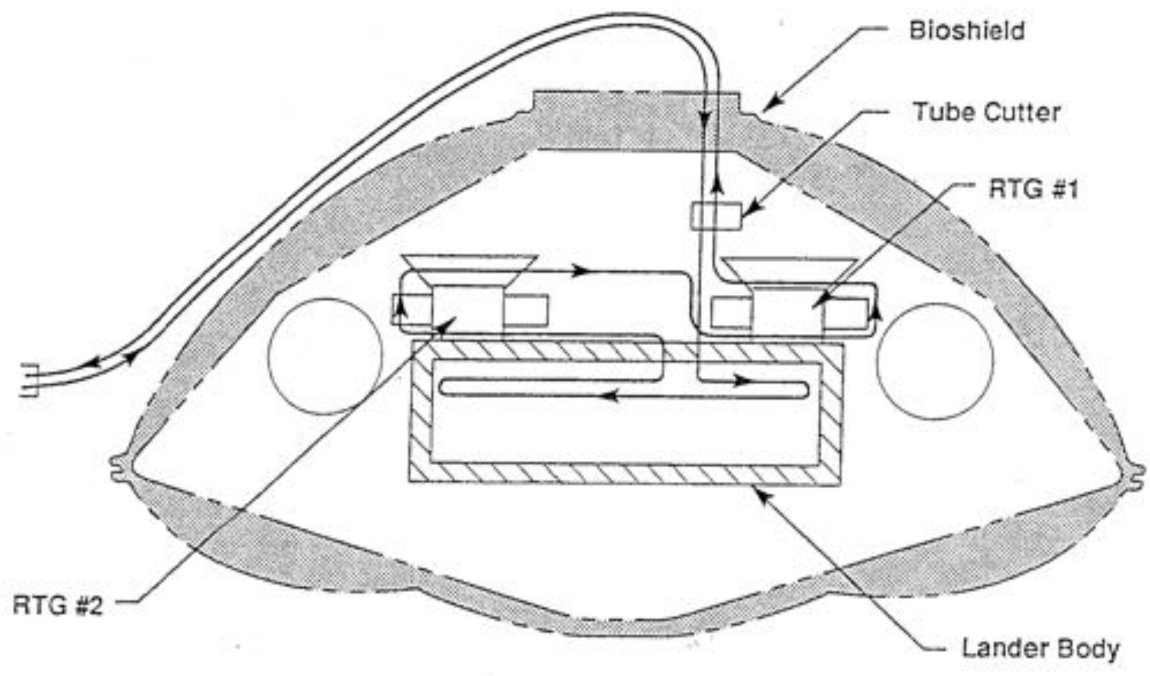

Figure 2.5 - Schematic Diagram of the RTG Coolant Loop to Provide Interior Heating Source During Sterilization

Heat compatibility testing of the TETM was accomplished by placing the vehicle in a large Oven and subjecting the vehicle to the thermal environments shown in Figure 2.6. Two different heating and cooling cycles were used in order to accentuate and evaluate the effects of the thermal stresses that the flight vehicle might encounter during terminal sterilization. During these thermal tests, the compatibility of the sporicide with the ground support equipment for the lander and the cooling loop was proven.

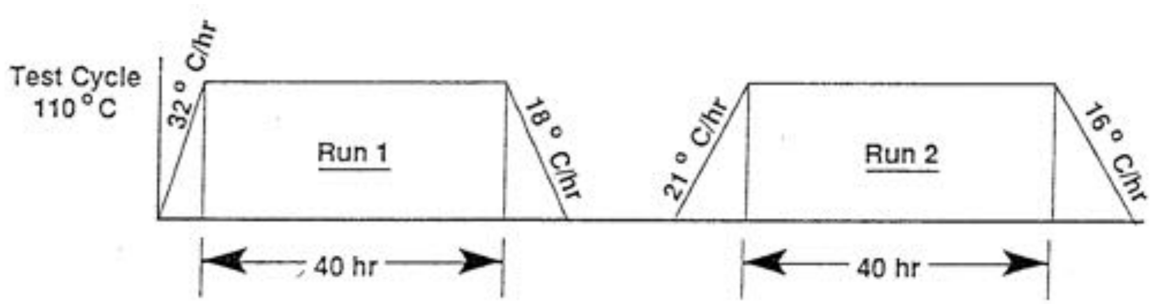

Figure 2.6 - A Graphic Illustration of the Two Different Heating and Cooling Cycles to Which the Thermal Effects Test Model Was Subjected

Other results of the TETM heat compatibility tests were: alinement was demonstrated not to be a major problem; thermal response, in general, was as predicted analytically: and outgassing of moisture and oxygen was not sufficient to alter the concept of sterilizing the vehicle in a dry, inert, gaseous environment, as defined in the Viking Sterilization Plan (moisture: 25% at 0C and 760 mm Hg when measured at the bioshield outlet; inert gas environment: 97% N,, 2.5% 0,, 0.5% other gases).

The second test vehicle was the Proof Test Capsule (PTC). The PTC simulated as closely as possible, at the component level, all flight-type units, Its use was to qualify the flight-type hardware in an integrated flight-type system by subjecting the vehicle to a series of tests and environments estimated to be more severe than what the flight hardware would actually encounter. The PTC lander was completely encapsulated in a bioshield cap and base. It was pressurized to 12.7 centimeters (5 inches) of water with sterile nitrogen gas. The flight landers were similarly pressurized during and after terminal sterilization and maintained at pressure until launch in order to prevent recontamination.

The PTC was subjected to the lander sterilization qualification test requirements. At the completion of these cycles, three components had failed nr exhibited anomalies and were removed from the PTC for investigation. The cause of failure was identified and corrective action was taken. The anomalies were not related to the sterilization cycle in any basic way.

2.3.6 Flight Vehicles

The two VLC's were assembled and environmentally tested at the prime contractor's facility before being shipped to the launch site. Upon receipt at the launch site, they were disassembled, inspected, and functionally checked to ensure the integrity of the hardware to perform the intended mission. During reassembly, bio-assays were performed to determine the biological load on each VLC. The results of these assays determined the duration of the terminal sterilization cycle necessary to satisfy both PP and scientific investigation requirements. Figures 2.7 and 2.8 show the terminal sterilization cycle imposed on VLC-1 and -2: respectively.

2.3.7 Organic Contamination Overview

The Viking organic contamination control experience that could apply to future missions would be that resulting from the requirements imposed to protect the organic science investigation to ensure the validity of the data obtained from the Gas Chromatograph Mass Spectrometer (GCMS). Organic contamination control activities on the Viking program were primarily a project-level, self-imposed requirement in order to ensure that the GCMS instrument would not receive or detect organic compounds brought to Mars on or in the Viking lander. There was an organic inventory requirement imposed on the Project through NPD 8020.1OA; this requirement was basically for the collection and storage of documentation and materials samples. The documentation consisted of information regarding the organic materials contained within the lander, the location of landing sites, and the condition of the lander after landing (successful landing or impact, impact velocity, etc.). The material to be stored was 50-gram samples of each organic compound present on the VLC in amounts exceeding 25 kilograms per compound.

The basic requirement that had to be satisfied was that the soil samples delivered to the GCMS experiment were each to contain less than one part per million organic material of terrestrial origin per the mission definition document. Early in the program, analyses were performed to determine the hardware requirements that would have to be imposed to satisfy the requirement that the sample delivered to the GCMS for evaluation would meet the allowable contamination level. These analyses indicated that: (1) the sample path hardware would have to be cleaned to one nanogram per square centimeter, (2) the sample path hardware would have to be sealed and pressurized after clearing to protect against recontamination, (3) the use of organic materials in the sample path hardware would have to be controlled and minimized, (4) the use of hermetically sealed devices would have to be implemented where possible, and (5) the sample path hardware would have to experience a hot helium purge prior to sealing and pressurization. The hot helium purge would reduce the residual solvent level below 3 x IO7 grams.

While the facility in Oak Ridge, Tennessee, could clean to the ten-nanogram-per-square-centimeter level, it would need to be upgraded to the Viking requirement. On the other hand, the White Sands Test Facility (WSTF) at Las Cruces, New Mexico, cleaned Apollo Lunar equipment to a certifiable level of one nanogram per square centimeter. The WSTF was selected since its existing capability was sufficient to meet Viking requirements. After discussions with NASA personnel in Houston and WSTF, the facility was made available for Viking use.

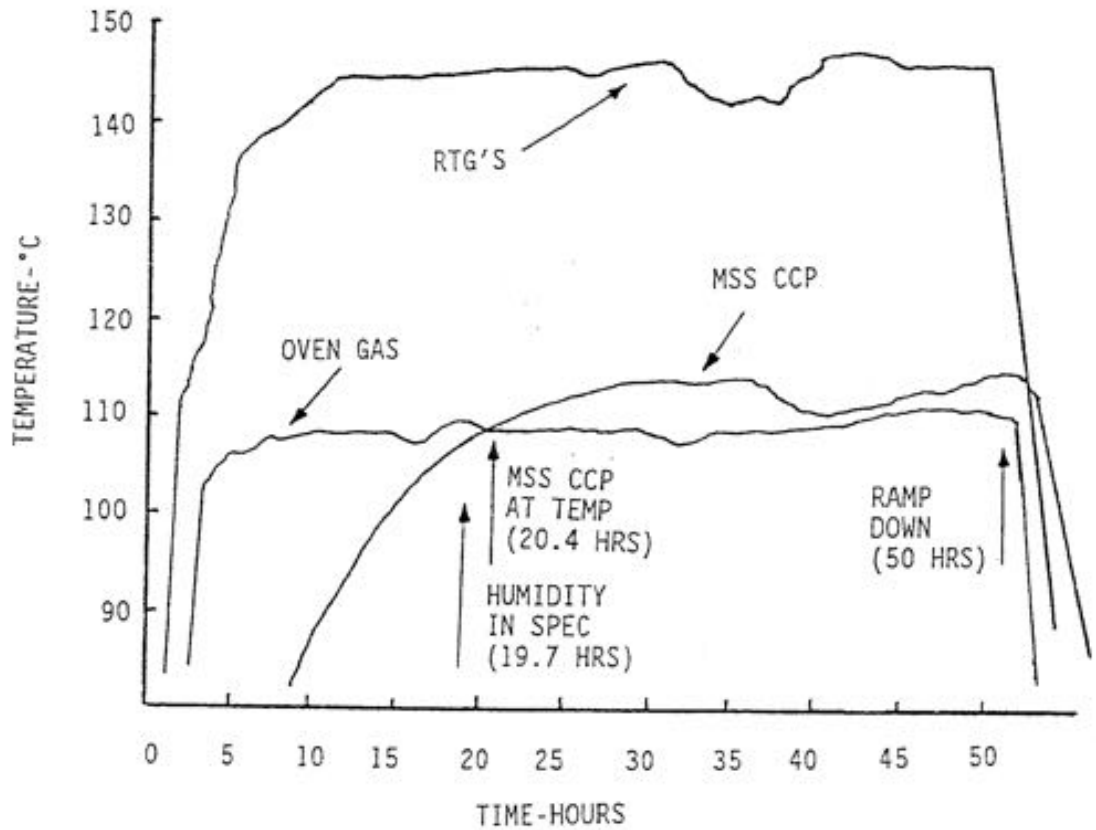

Figure 2.7 - Sterilization Cycle of VLC-1 (June 20-22, 1975)

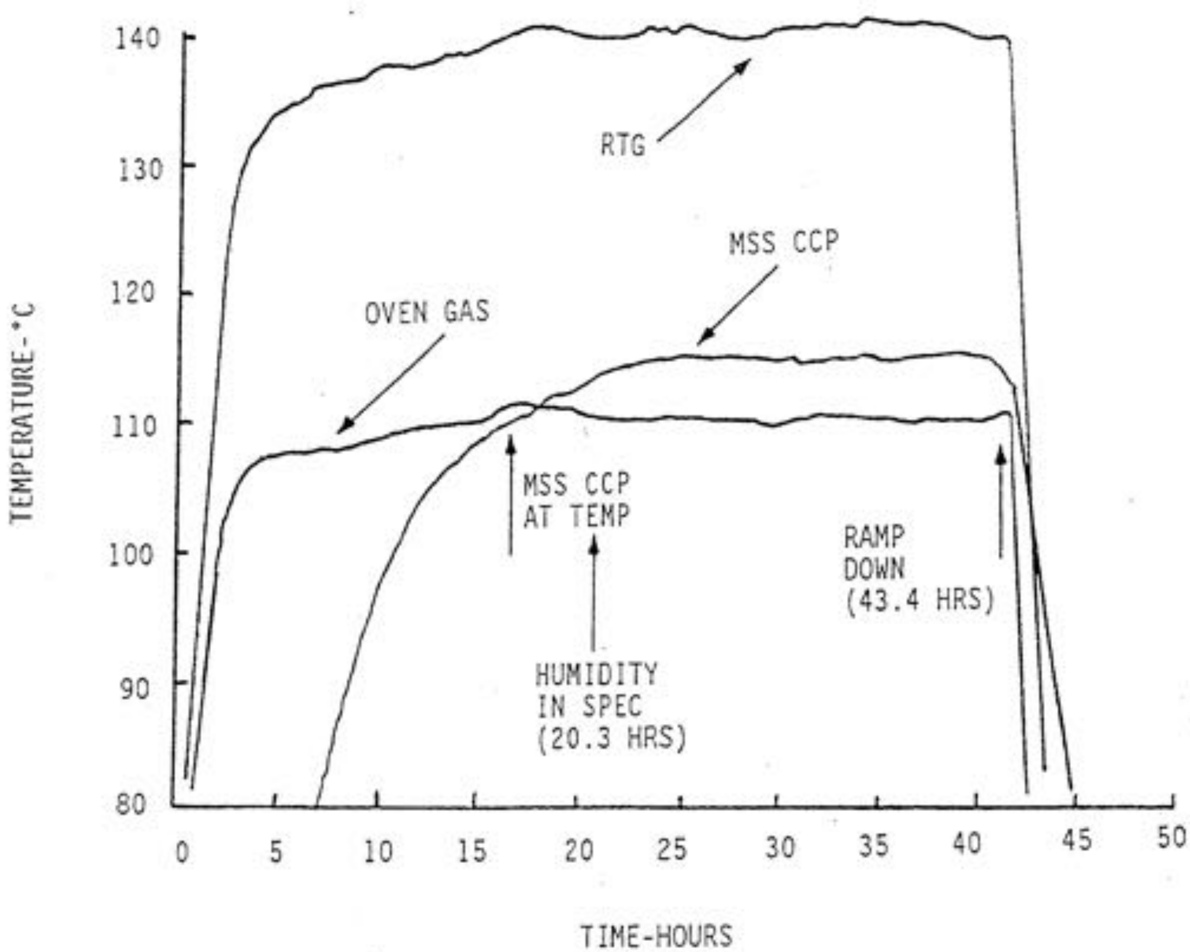

Figure 2.8 - Sterilization Cycle of VLC-2 (June 15-17, 1975)

In order to verify the approach taken and to better understand the possible impact on equipment design, several elements of prototype hardware and development hardware were processed through WSTF. The prototype GCMS Processor Distribution Assembly (PDA) subassemblies were processed to establish initial process requirements and determine cleaning solvent applications and processes. In addition, the Biology PDA prototype hardware was used as part of feasibility testing as was the Collector Head Shroud Unit (CHSU) for developing the hot helium purge system. The following design development hardware was processed through WSTF to improve/verify the cleaning process as well as verify design constraints/acceptability: (1) two [2] GCMS PDA's, (2) one [I J GCMS LPA, and (3) one [I] CHSU, The integrated GCMS PDNLPA was also cleaned at WSTF and utilized in the soil verification tests.

The following sequence of cleaning activities was verified as being acceptable to satisfy the overall organic contamination requirement. Upon receipt of the flight equipment at WSTF, it was disassembled and inspected for cleaning. The parts were then cleaned to the nanograde level by precleaning with detergents, isopropyl alcohol, trichlorethylene, or benzene/methanol. Final cleaning was accomplished by sonic cleaning in triple distilled freon TF in a 100-class clean room.

Reassembly, inspections, and flushing of the sample path- hardware was accomplished in the 100-class clean room. To verify the cleaning process particle count and the total hydrocarbon count, detail purges and flushes were conducted, The millipore methods were utilized for particle count and a final flush effluent was injected into the gas chromatograph (GC). A hot-helium purge was then used to remove residual solvent and the effluent was analyzed by the GC to verify cleanliness level. The typical flow for flight hardware processing is shown in Figure 2.9. Also, data from the Viking flight spare LPA is provided in Figures 2.1OA-2.1OD as examples of the data obtained during the hot-helium purge process.

2.4 TASK SUMMARY

The heat sterilization requirements defined for Viking were conscientiously implemented throughout the Project, and the spacecraft systems were successfully designed, developed, and assured to satisfy PP agreements and policies. Careful attention was paid to all design details and to the selection and application of materials and electronic piece parts. As a result, technology problems due to heat compatibility were minimized and resolved without major impact. The component development and qualification programs were also successfully completed, and the heat-compatibility test program associated with vehicle development served the purpose of establishing where problems existed so that all could be addressed and resolved within the allowable timeline. The Viking Project experience demonstrates that flight vehicles can be dry-heat sterilized with a high probability of success.

In conclusion, the Viking experience, with extremely sensitive instruments capable of performing in situ biological and molecular-analysis (organic ,chemistry) investigations of martian surface material, is felt to be directly applicable to MRSR missions. This is especially true if such missions incorporate biological or organic investigations but is also applicable in the case of other types of chemical investigations in which contamination might in some way reduce the validity or quality of the data product. However, the MRSR mission would have additional requirements imposed by the need to return a pristine sample to Earth, and new policy requirements and technical knowledge would be required beyond that reflected in the Viking experience.

The extent to which the Viking experience might be applicable to a MRSR mission is, however, &pendent on the extent and nature of the PP and contamination control imposed on a mission and/or the science requirements defined for its program. Each discipline should be evaluated early in the development of the program mission plan, and the specific requirements should be defined at that time so that they can be implemented into contract statements of work. It is probable that these requirements will, in turn, necessitate early technology developments to satisfy specific hardware

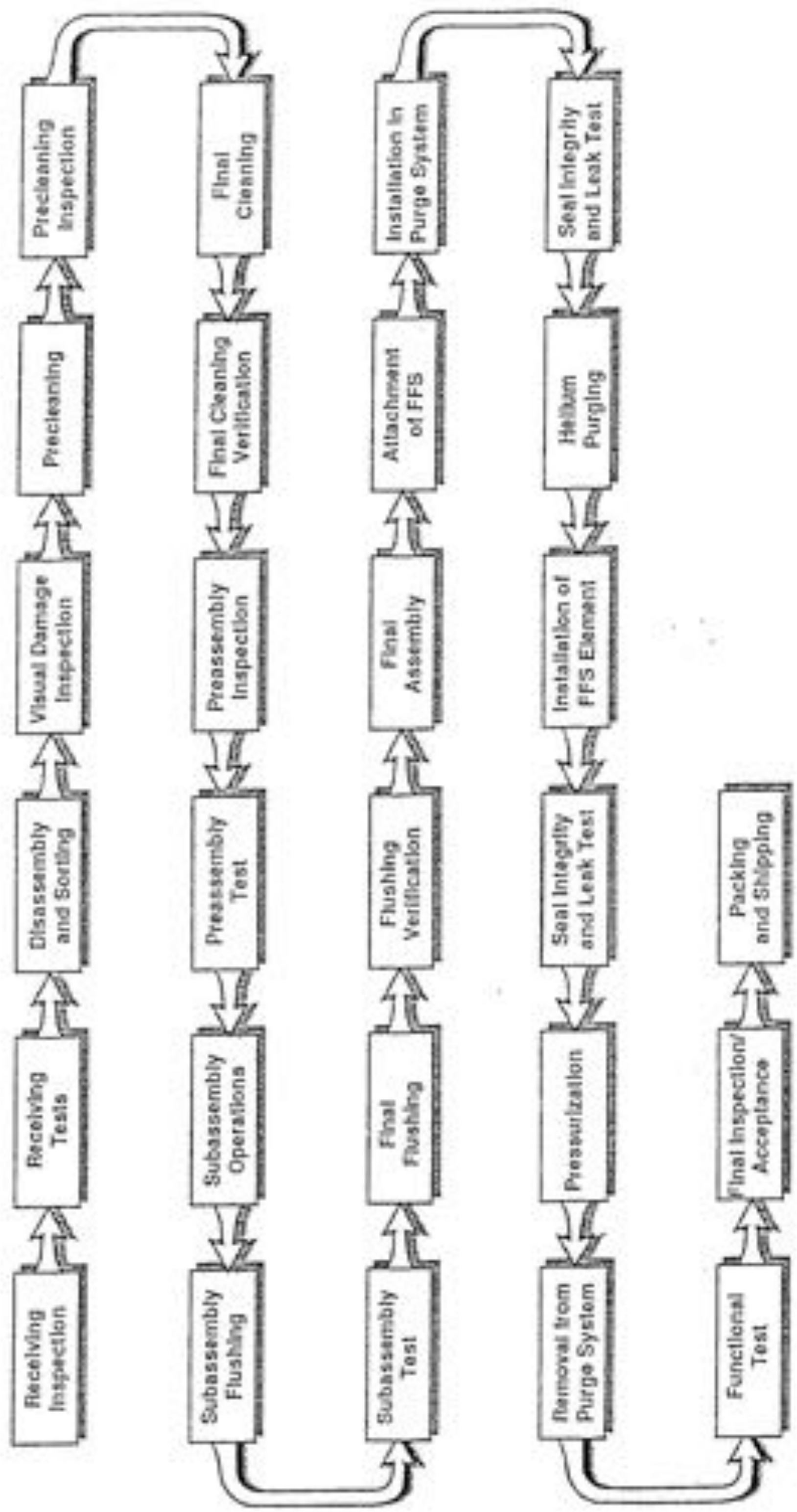

Figure 2.9 - Typical Flight Hardware Processing at WSTF

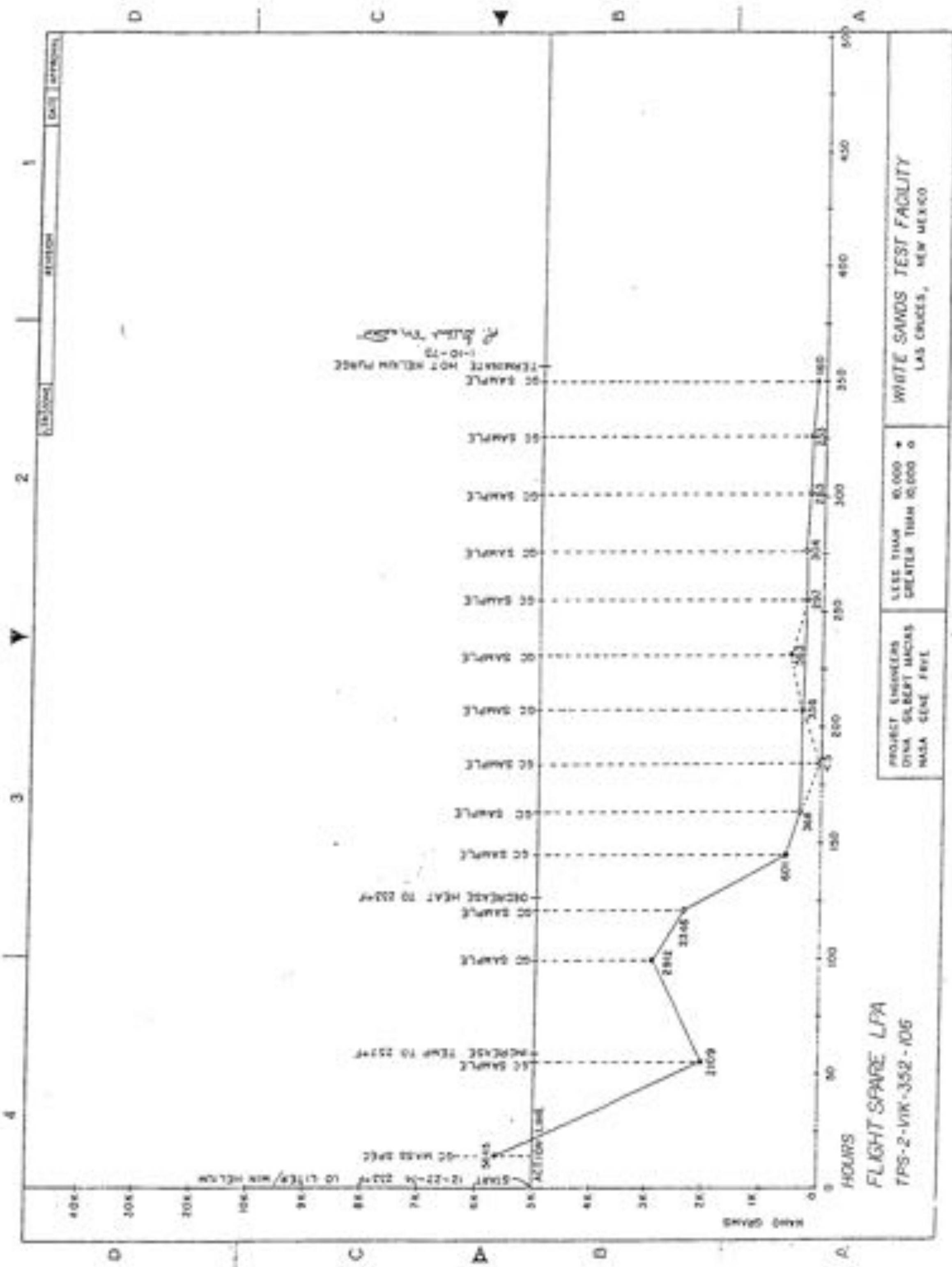

Figure 2.10A - Flight Spare LPA Hot Helium Purge History at WSTF

WSTF CHEMISTRY LABORATORY
VIKING PROJECT DATA SUMMARY

Hardware Identification: Flight Spare LPA
Begin Vacuum Purge : Dec. 17, 1974 1512
End Vacuum Purge : Jan. 10, 1975 1206

Vacuum Purge System No. : 2
Certification Chromatogram No. : 3296 - HP 31 A
Total Organics of Certification: 51.9 ng
Trap Used, S/N : 16

2 - VIK - 332 - 106 Steps 1 - 15

Chromatogram and Trap Number	Sample Date and Time	Sample Temp (°F)	Purge Time (hrs)	Total Organics (ng)	0 - 6 "Lights" (ng)	6 - 8 (ng)	8 - 10 Butene (ng)	10 - 12 (ng)	12 - 14 Acetone TF Freon (ng)	14 - 16 Isopropyl Alcohol (ng)	16 - 18 Pentane Benzene (ng)	18 - 20 1,4 Dioxane (ng)	20 - 22 Toluene (ng)	22 - 24 Xylene (ng)	24 - 26 → Minute Methyl Styrene (ng)
3323 - HP 31 A Trap Cert. 16	Dec.14,1974 0530			11.6			6.4		5.0						
3296 - HP 31 A System Cert. 16	Dec.18,1974 1240	222		51.9			12.2		39.7						
3332 - HP 31 A Trap Cert. 21	Dec.23,1974 0445			36.8	1.2		8.7		7.8		37.5		6.9		2.7
3334 - FM Hardware 21	Dec.23,1974 0600	222	13.5	3865.4	18.5		157.0		3714.5		87.7	253.9	582.9	28.3	372.4
3336 - FM MASS Spec. 21	Dec.23,1974 0835														
3345 - HP 31 A Trap Cert. 22	Dec.24,1974 1255			7.4			6.0								1.4
3348 - HP 31 A Hardware 22	Dec.27,1974 1310	222	54.5	2109.2	155.0		157.1		853.6		91.1	335.2	106.7	47.6	251.2
3338 - FM Trap Cert. 21	Dec.23,1974 1330			16.9					16.9						
3353 - HP 31 A Hardware 21	Dec.29,1974 0830	264	98.4	2911.9	495.0		20.20		1162.7		169.3	315.0	159.2	111.4	252.3
3308 - HP 31 A Trap Cert. 14	Dec.20,1974 1130			7.9			7.9								

Remarks:

Peak assignments are based on a comparison of retention temperatures and peak characteristics (shape and relative size) with mass spectral sample # 3336 - FM which was the GC/MS identification sample. (Trap S/N 21 was used again without certification from 3334 - FM - the quantitative sample).

Prepared by: Edward C. Fagget
Approved by: Jerry H. Schlett
QA : BR Field - 76-71

Figure 2.10B - Flight Spare LPA GC Data at Each Analysis Point

WSTF CHEMISTRY LABORATORY
VIKING PROJECT DATA SUMMARY

Hardware Identification: Flight Spare LPA
Begin Vacuum Purge : Dec. 22, 1974 1513
End Vacuum Purge : Jan. 10, 1975 1206

Vacuum Purge System No. : 2
Certification Chromatogram No. : 3356 - HP 31 A
Total Organics of Certification : 31.9 ng
Trap Used, S/N : 14

1 - VIK - 352 - 506 Steps 1 - 15

Chromatogram and Trap Number	Sample Date and Time	Sample Temp (°F)	Purge Time (hrs)	Total Organics (ng)	0 - 6 "Lights" (ng)	6 - 8 (ng)	8 - 10 Butene (ng)	10 - 12 (ng)	12 - 14 Acetone/Freon (ng)	14 - 16 Isopropyl Alcohol (ng)	16 - 18 Pentane Benzene (ng)	18 - 20 1,4 Dioxane (ng)	20 - 22 Toluene (ng)	22 - 24 Xylene (ng)	> 24 "Heavies" (ng)	Minutes
3367 - HP 31 A Hardware 14	Dec.30,1974 0815	256	171.5	2346.2	287.8		177.4		966.9		116.4	260.8	149.1	107.9	181.9	
3369 - HP 31 A Trap Cert. 14	Dec.30,1974 1130			< 5												
3375 - HP 31 A Hardware 14	Dec.31,1974 0805	231	145.3	601.3	53.7		64.4		240.9		49.8	48.8	52.0	33.9	57.8	
3381 - HP 31 A Trap Cert. 14	Jan.2,1975 1130			< 5												
3383 - HP 31 A Hardware 14	Jan.2,1975 1245	233	163.6	368.0			16.2		173.5		22.1	48.3	58.6	13.9	4.8	
3405 - HP 31 A Trap Cert 13	Jan. 1975 2320			14.8					14.8							
3407 - HP 31 A Hardware 13	Jan.4,1975 0845	230	207.5	335.7	26.8		23.7		102.6		19.8	43.8	71.7	30.5	17.0	
3409 - HP 31 A Trap Cert. 15	Jan.4,1975 1235			< 5												
3411 - HP 31 A Hardware 15	Jan.5,1975 0815	233	231.4	562.4	43.7		48.0		160.0		27.8	59.7	80.1	42.5	100.5	

Remarks: Peak assignments are based on a comparison of retention temperatures and peak characteristics (shape and relative size) with mass spectral sample # 3336 - SH which was the GC/MS identification sample.

Prepared by: [illegible]
Approved by: [illegible]
QA [illegible]

Figure 2.10C - Flight Spare LPA GC Data at Each Analysis Point

HSTF CHEMISTRY LABORATORY
VIKING PROJECT DATA SUMMARY

Hardware Identification: Flight Spare LPA
Begin Vacuum Purge: Dec. 22, 1974 1512
End Vacuum Purge: Jan. 10, 1975 1200

Vacuum Purge System No.: 2
Certification Chromatogram No.: 3296 - HP 31 A
Total Organics of Certification: 51.5 ng
Trap Used, S/N: 14

2 - 92K - 512 - 104 - Scans 1 - 15

Chromatogram and Trap Number	Sample Date and Time	Sample Temp (°F)	Purge Time (hrs)	Total Organics (ng)	0 - 5 "Lights" (ng)	5 - 8 (ng)	8 - 10 Butene (ng)	10 - 12 (ng)	12 - 14 Acetone or Freon (ng)	14 - 16 IPA (ng)	16 - 18 Pentane Benzene (ng)	18 - 20 1,4 Dioxane (ng)	20 - 22 Toluene (ng)	22 - 24 Xylene (ng)	> 24 "Heavies" (ng)	Minutes
3436 - HP 31 A Trap Cart. 24	Jan.6, 1975 0445			26.7	2.6		4.4		10.7						8.8	
3437 - HP 31 A Hardware 24	Jan.6, 1975 0800	233	255	297.0	20.0		6.6		75.2		22.1	46.5	76.3	32.8	5.3	
3447 - HP 31 A Trap Cart. 23	Jan.7, 1975 0045			13.6	3.3		8.0		1.3							
3452 - HP 31 A Hardware 23	Jan.7, 1975 0325	233	276.6	304.7	22.2		37.9		96.5		18.2	49.3	62.4	17.2	10.6	
3454 - HP 31 A Trap Cart. 23	Jan.7, 1975 1050			8.3			8.3									
3461 - HP 31 A Hardware 23	Jan.7, 1975 0655	233	303	263.8	18.8		15.4		70.7		21.4	48.2	61.6	14.1	13.8	
3463 - HP 31 A Trap Cart 21	Jan.8, 1975 1950			< 5.0												
3470 - HP 31 A Hardware 21	Jan.9, 1975 0735	233	316.8	233.2	19.6		14.8		49.2		19.8	40.3	38.1	14.7	36.7	
3472 - HP 31 A Trap Cart 21	Jan.9, 1975 1300			9.6	1.5		8.1									
3476 - HP 31 A Hardware 21	Jan.10, 1975 0345	233	350.7	150.1	16.1		10.8		63.6		17.7	24.1	23.3	2.2	2.4	

Remarks:

Peak assignments are based on a comparison of retention temperatures and peak characteristics (shape and relative size) with mass spectral sample # 3336 - FH which was the GC/MS identification sample.

Prepared by [signature]
Approved by [signature]
QA [signature] 3-6-75

Figure 2.10D - Flight Spare LPA GC Data at Each Analysis Point

3.0 TASK 2 (2.2 of SOW)

This section presents the results of work defined in Task 2.2: debrief selected Viking project, engineering, and science participants for opinions and insights into pertinent lessons learned from Viking planetary protection (PP)' and contamination control experience. The individuals interviewed represent a vertical cross section of responsibilities, from top management to technical specialists. This broad awareness of PP requirements ultimately assured a successful implementation of the PP requirements set forth by NASA and the international science community. The members of the Viking Project Team, each in some way, helped to define the procedures and specifications or develop the systems and methods needed to help the Viking Project meet PP requirements. The debriefings have been only superficially edited, and the statements/opinions are those of the interviewees/interviewer.

3.1 PURPOSE AND NATURE OF WORK

Even as the Viking mission plan began to take shape during the mid and late :95O's, ER international debate had established a unique set of requirements the Project would ultimately have to satisfy while preparing itself for the exploration of Mars. The international space science community, represented by COSPAR, was concerned about the potential for contamination (biological and organic) of other bodies in the solar system by spacecraft from Earth. In an attempt to protect the pristine environment and potential biosphere of Mars, as well as the surfaces of other bodies, COSPAR developed and sought agreements that ultimately led to the creation of NASA policies to guide the establishment of spacecraft requirements that could satisfy PP.

As Viking mission planning evolved, however, it became apparent to many that satisfying PP alone was not enough to ensure the integrity of data acquired by instruments designed to search for evidence of exobiology, which involved the use of automated, extremely sensitive life-science or organic- analysis experiments and sample acquisition systems. Both kinds were represented in the Viking science payload. Therefore, those Viking spacecraft elements designed to enter the martian biosphere not only should not contaminate the martian environment, but the biology and organic chemistry instruments also had to be so sterile or clean that there could be virtually no chance of contaminating the results with evidence of organisms or organics that may in :act have been transported to Mars aboard the spacecraft.

The solution was to impose "uncompromisable" decontamination procedures for all of the lander elements and then even stronger requirements for the most critical exobiology instruments. In addition to the use of meticulous cleaning and clean-room assembly methods, the dominant methodology utilized was whole-system, dry-heat terminal sterilization. Commitment to this procedure meant that every material, part, and component had to be heat-qualified and assured to be fully tolerant of the time/temperature regime used during terminal sterilization, which in turn implied that heat compatibility had to be technically understood and required from the very moment component design and 'Officially, the name of this function has been changed by NASA from "planetary quarantine" to "planetary protection.' However, the former term is still quite popular and is often mixed in use with the new term, suggesting that they represent different policies or concerns. Such is not the case. In preparing this document, all uses of the older term not reflected in direct quotes have been changed to the new term development was undertaken. Because the fully assembled spacecraft would be sealed and pressurized for terminal sterilization, and had to be maintained in that configuration to prevent recontamination, any component failure that required disassembly as a result of sterilization would negate the entire procedure at the most critical point in the launch schedule. Proof of the Project's success in dealing with this PP challenge is readily visible in the performance and achievement of the mission itself, and this report presents personal accounts of how it was accomplished.

3.1.1 The Viking Project

The Viking Project was managed for the National Aeronautics and Space Administration by the Viking Project Office (VPO) at NASA's Langley Research Center (LaRC), Hampton, Virginia. A precursory program for a Mars lander mission, Voyager, had evolved through its conceptual mission definition phase during the mid 1960's, but the Voyager-Mars mission was found to be too large in scope and cost.

The launch vehicle selected for each of two Viking flight spacecraft was the Titan IIIE (T3E), a new configuration of- the USAF/Martin Marietta T3D but with General Dynamic's Centaur upper stage. Three Viking flight spacecraft were specified by the contract, one of which was defined as a backup should either of the two scheduled for launch suffer a last-moment failure during or after terminal sterilization just prior to launch. This backup was believed to be a critical requirement because both of the Viking T3E's had to be launched from the same USAF Cape Canaveral launch pad within a period of less than three weeks of each other, making it extremely difficult to both replace a failed component and resterilize the spacecraft in time to make the launch window.

Caltech's Jet Propulsion Laboratory (JPL) in Pasadena, California, largely a NASA facility dedicated to the development and operation of unmanned spacecraft designed for scientific missions, had responsibility for the Viking orbiters as well as flight and mission operations (utilizing JPL's control center and NASA's Deep Space Network). in addition to these major Project team members, a Viking program office at the NASA Headquarters had oversight responsibility for NASA while contractors were selected from across the country to provide materials, parts, components, and science instruments for the Viking Spacecraft systems.

Among the science instruments planned for the Viking landers were a life-science package that ultimately contained three independent biology experiments to look for life on Mars and an extremely sensitive molecular analysis package designed principally to detect organic compounds. The molecular analysis package was also capable of performing precise composition analyses of the martian atmosphere. The development of these two instrument packages ultimately proved so challenging that each was essentially given the degree of focus and effort normally attributed to an entire spacecraft. Each one, the Viking Lander Biology Instrument (VLBI) and the Gas Chromatograph Mass Spectrometer (GCMS), severely tested NASA's PP resolve while establishing demanding standards in the area of contamination control associated with: (I) lander vehicles, (2) their system components (electronics and fabrication materials), and (3) science instruments designed to look for evidence of life and/or organic chemistry elsewhere in the solar system.

In the following text, which reflects the response of participants interviewed as defined for Task 2.2 in the NASW-4355 Statement of Work, the content is structured in the following manner: (A) an overview of the Viking program that focuses on those problems, activities, and events that were directly or indirectly influenced by the impact of PP requirements and procedures, and which represents homogenous rather than individualized opinions of such influences; (8) pertinent statements by specific individuals in authority during the chronological period of Viking program and mission activity; and (C) a composite of the most significant recommendations suggested by those interviewed.

A few of the former Viking Project personnel sought for debriefing could not be found or were unable to respond, having retired or relocated to unknown places or moved up into demanding positions of high-level responsibility in NASA or industry. However, the names reflected in this report represent an important and significant memory base associated with the team that existed at NASA's LaRC Viking Project Office, JPL, and MMC/D (and including others who were not associated with these major team members). The listing in Figure 3.1 gives the names of those who participated in the debriefing interviews and reflects their professional responsibility during the period of their association with the Viking Project. Some of those queried were sought out to provide important points of insight with respect to more specialized issues and are, therefore, identified as supplemental participants in association with principal contributors.

3.2 OVERVIEW OF PLANETARY: PROTECTION INFLUENCE ON VIKING PROGRAM

Simply stated, NASA originally defined PP (reference NHB 8020.12/12A, 1969) as: "The avoidance of contaminating the biosphere of a planet with terrestrial life forms so that the ecology of a planet is maintained in its pristine state during the period of scientific investigation." NHB 8020.12 established NASA's fundamental requirements for biological protection in accordance with NASA Policy Directives NPD 8020.7 and 8020.1 0. These NASA policies and requirements were developed in a manner consistent with objectives recommended by the Committee on Space Research (COSPAR), the representative office of the International Council of Scientific Unions.

The resulting agreement is defined in Article IX of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space (Including the Moon and Other Celestrial Bodies), Jan. 27, 1967, UN Doc A/RES/2222/(XXI), TIAS +6347. The agreement has been interpreted to be effective for a period of 50 years, beginning in 1968 and ending in 2018, to afford an adequate opportunity to resolve the question of whether there is life on Mars. It should be noted, however, that the 50-year period has never been well defined-and could be extended, due to the fact that it was based on a mission-opportunity rate (to study the biology question) that is much greater than what has been realized or than may be necessary due to new knowledge.

INTERVIEW PARTICIPANTS

Viking Project Office, NASA/Langley Research Center

James S. Martin, Jr., Project Manager; Dr. Gerald A. Soffen, Project Scientist; Israel Taback, Technical Deputy & Chief Engineer; Leo P. Daspit, Planetary Quarantine Officer: Charlie King, materials and processes; Ansel Butterfield, electronic parts qualification (General Electric),

Viking Program, Martin Marietta Corporation, Denver

Walter 0. Lowrie, Program Manager; John D. Goodlette, Technical Deputy and Chief Engineer; Richard G. Adamson, Viking Finance Manager; Harrison Wroton, Resident Manager for the Biology Instrument at TRW; Dr. Benton Clark, XRFS/Inorganic Science Team (instrument developed by Martin Marietta, Denver).

Biology Science Team

Dr. Harold P. Klein, Biology Team Leader, NASA Ames Research Center; Dr. Norman H. Horowitz, Pyrolytic Release Principal Investigator, California Institute of Technology/JPL; Dr. Gilbert V. Levin, Labeled Release Principal Investigator, President, Biospherics, Inc.; Mr. Ron Gilji, VLBI Technical Manager & Asst Team Leader, TRW.

Molecular Analysis (Organic Chemistry - GCMS)

Dr. Klaus Biernann, Team Leader, Massachusetts Institute of Technology; Dr. Dale Rushneak, GCMS Principal Technical Manager; G. Calvin Broome, Project Lander Science Instruments Manager and (later) Extended Mission Project Manager/Mission Director (at JPL), NASA/LaRC; and Joseph C. Moorman, GCMS Program Manager, NASA/LaRC.

Jet Propulsion Laboratory

Mr. Kermit Watkins, Orbiter Program Technical Deputy and (later) Continuation Mission Project Manager; Alan R. Hoffman, Supervisor, Planetary Quarantine Analysis; and Robert Mitchell, Orbiter Navigation Team.

Additional Interview Contributions

Dr. Joseph A. Stern, President, The Bionetics Corporation (former Manager of PP Contract Support, LaRC-VPO contractor); Dr. Richard S. Young, Viking Program Scientist, Exobiology Manager and Planetary Protection Officer, NASA Headquarters; Dr. Donald L. DeVincenzi, currently Space Science Division, NASA/Ames Research Center, succeeded Dr. Young at NASA Headquarters and was responsible for reviewing PP with respect to Viking orbit changes during the Continuation Mission (as orbital periapsidies were lowered!.

Figure 3.1 - Listing of Debriefed Viking and NASA PP Personnel

Much of the research associated with PP was conducted during the period in which the Voyager-Mars conceptual mission was under study. It was during this period that sterilization methodologies were carefully evaluated in association with research concerned with determining the probable bioload on and in a surface-impacting or landing vehicle. Out of this work came a number of calculation models that could be utilized for determining the Probability-of-Contamination (PC) and the Probability-of-Growth (PJ for Earth organisms that might survive transit to Mars, as well as the predicted success for candidate sterilization methods. The international agreement states that the cumulative probability for the contamination of Mars by Earth organisms shall be no greater than one chance in one-thousand ($1x10^3$) during the period of biological interest. However, the issue is complicated by the fact that requirements for a specific mission, Viking for example, may be made more severe by self-imposed constraints to further limit the chances of contamination in/of exobiology science instruments. In effect, this makes it possible for organic and biological contamination control to impose requirements that are significantly more difficult to achieve than the PP requirement alone.

Among those most knowledgeable about this precursory work and the period in which it was conducted, much of which was done at the Jet Propulsion Laboratory and the Kennedy Space Center during the early and mid-l96O's, there is broad agreement that the research was extremely comprehensive and successful in what it sought to accomplish. It successfully identified satisfactory methods for determining the spacecraft bioload as well as the contamination, survival, and growth probabilities for organisms on the spacecraft, thereby making it possible to arrive at reliable project planning decisions pertaining to mission and spacecraft design--as well as spacecraft sterilization--that was respectful of PP policy. None of the principals with expertise in this area felt it would be necessary to conduct this kind of work again, even in light of improved technical capabilities for doing it: They cited the Project's highly documented success during development and mission operations as the final vote of verification for the work and suggested that it was sufficiently applicable to future mission considerations to serve as a highly adequate database and foundation for similar decisions.

Only at a point when specific new missions and spacecraft systems are defined is it likely that new research will be needed to contend with those requirements that are peculiar to the new program. Even then, the Viking experience reflect the best paths for satisfying PP requirements prior to launch. For example, there is consistent agreement that the best probable way to achieve pre-launch PP readiness will still be with dry-heat sterilization. Similarly, the best method of application will still be that of heating the whole system, following appropriate qualification and acceptance testing to ensure the heat-compatibility of spacecraft materials, parts, and components, just as it was for Viking. And finally, it is likely that the spacecraft element(s) to be landed on the surface of Mars will be contained. in some sort of in-flight discardable or separable bioshield not unlike that used to protect the Viking descent capsule against recontamination following sterilization.

The work that led to the decisions crucial to designing the Viking mission sequence and lander system produced strongly defined conclusions as a very reliable basis for those decisions, suggesting that it is unlikely, at least in the foreseeable future, that new methods will be any easier or less costly to utilize. Indeed, the Viking experience seems to suggest quite strongly that the alternatives would be more costly, more difficult to undertake, and probably would not produce any real benefits over what dry-heat sterilization achieves, simply and economically in comparison. While heat compatibility will probably continue to be a concern that must be addressed when using this mode, it is not as great a problem as those encountered using other modes of system-level sterilization.

3.2.1 Philosophical Debate: PP - Past, Present, and Future

Philosophical concerns were clearly important to several of the key people interviewed for this report. The need for sterilization was strongly debated prior to the Viking Project, and the arguments favoring the need for sterilization during that debate are still very much in evidence today. Moreover, those who must deal in philosophical concerns with respect to future missions are inclined to believe that the issues which drove the need for Viking lander sterilization will become even stronger drivers in the future. There were--and still are--two major arguments for sterilization: (1) the PP requirement to protect other bodies in the solar system against contamination by Earth organisms that might be transported by spacecraft, including vehicles that do not land on or impact the planet; and (2) the need to achieve severe decontamination objectives and then prevent recontamination of the sample path or instruments involved in exobiology (biological and organic chemistry investigations). A third issue, and perhaps the one most likely to generate philosophical debate and new policy requirements in the future, is that of sample return and back contamination.

During the 196O's, noted scientists like Joshua Lederberg and Carl Sagan argued strongly for policies and technical approaches that would reduce to very small chances the opportunity for spacecraft-borne Earth organisms to reach the surface of Mars. It is now believed by many of the "Viking alumni" that the success of those arguments was due to their use of mathematical probabilities that made it seem virtually impossible to suggest that a planet's surface could not be contaminated by Earth organisms, no matter how hostile the planet's environment is to that possibility.

The counter argument was perhaps voiced most strongly during that period by one of the Viking biology experimenters, Dr. Norman Horowitz, who believed (and still does) that total sterilization was unnecessary. He contended that Earth organisms could not survive, grow, or propagate on the martian surface. While he was not successful with his argument at that time, it is perhaps a major—but popularly muted--contention among exobiologists today, based on Viking results, that Mars may even in fact be a more hostile place for Earth's microorganisms than anyone had previously imagined; that the ultraviolet (UV) flux, together with the highly destructive oxidizing chemistry believed to have been detected in the surface material, make it all but totally impossible for Earth organisms to make the transition to Mars' surface--even if reasonable populations manage to survive aboard a generally unsterilized spacecraft. In other words, the counter argument (then and now) suggests that even a relatively "dirty" spacecraft is extremely unlikely to contaminate the surface of Mars. Of even greater significance for future missions, however, is the fact that this argument also suggests that Mars organisms, should they exist and having evolved to survive in that chemically destructive and irradiated martian environment, would find it equally difficult to survive a transition to Earth. Dr. Horowitz suggests that they would be so unique that they would find Earth as deadly for them as any Earth organism would find Mars,

It should be noted, however, that Dr. Horowitz and others who make this argument do not advocate sending unclean spacecraft to Mars; only that they need not be sterilized to the extent imposed on the Viking landers and aeroshell components. Dr. Horowitz, who participated in these debriefing interviews, acknowledges that instruments comparable to the Viking VLBI and GCMS instruments must certainly be cleaned and sterilized to the extent that the Viking instruments were to assure that their data products are not corrupted by organisms or other possible organic contaminants inadvertently brought to Mars aboard the spacecraft. Beyond that requirement, Dr. Horowitz and others feel that cleaning and clean-assembly methods would afford an adequately decontaminated spacecraft for future Mars missions.

While many of those associated with the Viking Project have a tendency to agree to some extent with Dr. Horowitz's argument, whether their expertise is scientifically or technically motivated, they feel that "the reality" which essentially dictated Viking decisions in spite of such arguments will, in all probability, drive similar decisions even more strongly in the future. Future Mars missions will surely attempt to place landers, rovers, paratrometers, etc. in locations on the surface where there is evidence of possible liquid water in the past or presently frozen water. Also, it is not known if the highly oxidizing soil covers the entire planet. Future missions will attempt to explore areas where organisms have a better chance of surviving. Moreover, it is argued by some, including Dr. Gilbert Levin, another Viking biology experimenter who participated in this debriefing, that there still is no direct evidence that the martian environment is as hostile, chemically, as Dr. Worowitz and others have suggested on the basis of their interpretation of the Viking biology results. For example, if the surface material is not as deadly as suggested, organisms may need to do little more than burrow into it in some fashion to hide from and survive the UV radiation environment--assuming they can then find the resources they need to live and possibly grow.

And, indeed, several of those interviewed pointed out that new debates--on an international scale--already demonstrate That the world's science community is not yet ready to write off the biology issue with respect to Mars. Moreover, there already is a growing sentiment in the international community that we must do all that we can to keep the martian environment as pristine and uncontaminated as possible. This, in turn, suggests that PP concerns are likely to be as strong as ever in dictating cleanliness and sterilization specifications for future Mars spacecraft in terms of biological and/or organic contamination control.

3.2.2 Viking Experience

The Viking experience illustrates both the nature of that impact and how it might be most effectively addressed. .Because sterilization technologies had been studied very intensely prior to start- up for the Viking Project, the anticipated impact of heat sterilization was also fresh in the concerned minds of the technical and management authorities responsible for deciding how it might be achieved and in what manner the appropriate procedures should be implemented. There was some uncertainty about what the actual sterilization intensity should be (temperature versus time), making the perception of the problem somewhat worse. PP requirements for sterilization noted only that 100C should be, considered the minimum temperature at which lethality could be achieved, but those involved in research to determine a satisfactory time/temperature regime for heat qualification testing for parts and components were proposing temperatures as high as 145OC.

Electronics engineers, in particular, were very concerned that it would be extremely difficult, if not impossible, to design certain kinds of electronic components and circuit boards that could withstand such temperatures. Materials engineers were concerned that some of the materials they might ordinarily use could not tolerate sterilization temperatures at all and that it might be very difficult to find alternative materials to replace them. Also, it was anticipated that some materials-even heat-tolerant metals-- might not be compatible with each other due to different rates of expansion and contraction associated with the application of heat. Even familiar problems like creep, associated with fasteners, were found to occur at lower temperatures than expected and were, therefore, more common in the case of Viking. There also was concern that some materials--particularly those involved in fabrication processes-would develop weaknesses that would cause them to fail prematurely or under stress or that they might produce volatile contaminants (off-gassing) that would be unacceptable in a science environment that could be corrupted by their chemical product.

For these reasons, the Project was inclined to give technical issues that evolved out of PP a high priority rather than underestimate their impact. All of the concerns were very real, of course, whether viewed by Project management at NASA/LaRC or by those working in Denver on Martin Marietta's Viking Lander Program. As a result, a great deal of intense, coordinated work was done to evaluate the impact of heat soaking and to try to find solutions well ahead of hardware requirements for the program.

Extensive research was conducted to identify those components in which significant impacts could be anticipated: e.g., when conventional materials could not be used, as in the case of the battery packs or in potting compounds used in electronic applications. Breadboard components were built very early .in order to study some of the problems expected to be most critical, particularly with respect to electronics--parts that could break due to heat stress and solders which lost their integrity when heated. New procedures were designed for testing, qualifying, and acquiring parts or materials; and searches were conducted to find fabrication processes or materials that would remain sufficiently stable when heated. In the end, heat-compatible alternate materials were found, fabrication processes were developed that could withstand heat qualification and sterilization temperatures, and both Viking Lander Capsules successfully completed their terminal sterilization procedures without need for recycle.

3.3 DEBRIEFING COMMENTARY

The purpose of the debriefing interviews was to suggest, through personal recall, what the Viking experience with PP policy and its technical impact affords in the way of broad applicable knowledge for future programs which may have to address similar challenges. It's clear, as a result, that hindsight can produce both consensus and divergence in the perceptions of what was learned from the Viking experience, so it is appropriate to express these views in order to better understand and appreciate the value of that experience. In addition to the recall and views expressed in this section, additional comments may be included in Section 3.4 for a few of the key people (Issues and Recommendations).

The PP impact was significant and pervasive, particularly in respect to the selection of parts, materials, and processes required in the fabrication of the lander systems. Many of those that might have beer; used conventionally could not tolerate the heat-soak sterilization temperatures, and alternates had to be found. As a result, it is largely the process of requiring rigorous heat compatibility acceptance testing, qualification assurance, and, finally, component- and then systems-level thermal and operational verification prior to spacecraft assembly for terminal sterilization that made the Viking experience with PP a success story.

It is less clear to what extent the heat compatibility specifications contributed to the overall quality and success of the lander systems. The majority of those interviewed believe that the severe requirements imposed--particularly on electronic components--may very well have afforded greater "spacecraft margin" in terms of reliability and longevity, a perception strongly supported by the technical/scientific performance success and the long life of both Viking landers. Almost as a single voice, however, there was a strong sense of unanimity with respect to the success and importance of the test and qualification process implemented on the Viking lander program. The qualification process was driven to its high standard of performance by--at least in part--the heat-compatibility specifications established to ensure that the system could safely survive the critical terminal sterilization procedure.

In summary, those interviewed concur that the effort to provide firm and clearly defined requirements at a very early stage of the Viking development program contributed significantly to the overall success of that program, in spite of the fact that it involved new and untried technical or management concepts that produced a few implementation problems before the Project participants were comfortable with the relationships and procedures involved.

3.3.1 Interview Summaries: Management

3.3.1.1 James S. Martin, Jr., Aerospace Consultant

Mr. James S. Martin, Jr., presently an aerospace consultant, has had an extensive career in the aerospace industry and with NASA. Following 22 years with Republic Aviation, he moved to NASA's Langley Research Center and eventually served in a project management position for the highly successful Lunar Orbiter program. He was later assigned to what was then known as the Voyager (Mars) Program in 1967 and was ultimately named as the Project Manager for the revised program that was to bring that concept to reality--the Viking Project. He has since served in top management positions with Martin Marietta Corporation in Bethesda and Baltimore, Maryland.

The issues associated with PP were recognized early in the thinking process concerned with a Mars lander mission, "although we didn't recognize, probably, the magnitude of the activity that would be required." Nor did the Project recognize the full impact of the decontamination issue, at least in terms of how PP requirements would interact with the more demanding requirements imposed by the biology investigation. In spite of the early technical concerns, however, one could make a point that having these requirements probably did increase the reliability of almost all of the affected components--those usually the most vulnerable to heat. So meeting the PP requirement did enhance the reliability of the components: "better parts make for a better machine." Because a PP requirement like the one Viking had to contend with has a characteristic of extending itself into almost every phase of the program and mission, it becomes a major overriding kind of requirement that needs to be understood early in future programs.

By the late 19603, dry-heat terminal sterilization of the Viking Lander Capsule (VLC) seemed the best way to go about it, assuming that the parts and components could be qualified. "Compared to other schemes we looked at, it is a pretty simple process as long as the stuff will take the heat.' That is, if you heat things for the right amount of time, "you have a very good probability of sterilizing the lander, the sample path, whatever it is you're trying to sterilize.' In addition, you're not dependent upon an individual technician to maintain consistent cleaning procedures throughout the spacecraft; heat essentially soaks into the entire spacecraft 2s a single, continuous process, without favoring any part of it, until even the most inaccessible, deeply insulated (coldest) component is warm long enough to be sterilized. And in the process, it's safe; it does not involve potentially destructive or toxic chemistry or hazardous radiation. Without question, "some good analytical research work was done to arrive at dry-heat sterilization methodology, and there's no reason I know of why it wouldn't be valid today."

A major program like the Viking Project can get into trouble if the management offices fail to work well with each other, but that wasn't a significant problem for Viking. PP needs to be implemented as firm, well defined systems-level requirements, because 'if they're uncertain and changing, that can have a major impact on design and development activities." The appropriate kind of implementation requires a strong, positive working. relationship between the management agencies, e.g., the Viking Project Office at Langley and NASA Headquarters. In some of the major relationships between projects and Headquarters today, "I sense an almost adversary kind of arrangement." That was not the case for Viking. NASA Headquarters was involved in all of the activities that the Project was involved in. "I think they were made aware of everything going on, and I feel that they were a valuable member of the team; as such, they were as committed to succeeding as the Project was, and I think that was very helpful." That's how it should work: "NASA Headquarters [program office] should have an oversight and monitoring role, but it should not be an adversary role."

If there was any concern at all about our interaction with NASA Headquarters, it was only because "everyone was feeling their own way" as we were getting started. It was, after all, the first time this kind of thing had been undertaken in terms of sterilizing an entire spacecraft. "Hall (Larry Hall, Planetary Quarantine Officer at NASA Headquarters during the Viking era) and his people had a problem in understanding how to interpret COSPAR's requirement--what it really meant; what was the right thing to do [policy] from NASA's standpoint.' Indeed, PP wasn't a nice, well defined requirement that one could then sit down and manage or resolve with ease. But once it was better understood and we'd found ways to successfully address some of the key problems, our confidence grew and we became a very effective team.

3.3.1.2 Walter 0. Lowrie, Aerospace Consultant (retired President, Missiles & Electronics Group, Martin Marietta Corporation, Orlando, FL)

Supplemented by (1) Richard G. Adarnson, Vice President, Business Development, Martin Marietta Corporation, Bethesda, MD, was Business Manager for the Viking Program in Denver; and (2) Harrison "Hatch" Wroton, Director of Engineering Excellence at Martin Marietta's space systems group in Denver, was Director of Science Systems Subcontracts and then served as Biology Instrument Manager for the program resident team at TRW.

Walter 0. Lowrie, the former Viking Program Manager for Martin Marietta Corporation in Denver, first worked on the Viking program during the pre-bidding phase, with responsibility for defining launch and flight operations as well as the test program. The PP function ultimately reported to him as well. He left the program for other responsibilities but returned to it later, first as deputy program manager and then as its manager and a division vice president.

When preparing to bid for the Viking contract, program management had been convinced [reference, J. A. Stern, this section] that dry-heat sterilization was the best way to satisfy the Viking PP requirement. However, the proposal team was not actually sure at that point which way the customer wanted to go. Other methods remained under study, just in case, but everyone was focused on system-level heat sterilization. For a time, there was a feeling of uncertainty because of the ongoing debate over how severe the temperature-versus-time regime should be for the various test levels of acceptance and qualification, and to what extent it might be compromised before it could be well understood in terms of technical impact. The temperature specifications did go down, in fact, and may have gone down some more if the biology team had not stepped in to reflect their concern; their expressed feeling was '...we must be sure we don't contaminate the biological instrument." The final specifications for terminal sterilization were really guided more by the biology contamination control issue than by the PP requirement.

With respect to PP, "the biggest thing that sticks out in my memory is the tremendous impact on materials.' The engineering community had predicted that the materials selection process would feel the greatest impact, "but I guess I've got to say, in all honestly, we didn't realize how big and how extensive it really would be or the subtlety of what it would do to all of the subsystem equipment." Because of the systems-level implementation, specific PP impacts are difficult to distinguish from new technology issues, but the selection of materials and parts was particularly critical and seemed to be very strongly affected by the heat sterilization requirement. Virtually all of the electronics were affected and materials had to be changed in many cases.

"PQ pervaded or invaded the whole program's structure, because the parts and materials qualification issue tested the philosophy for parts, materials, and components all the way on up through the TETM [thermal effects test model] and PTC [proof test capsule] programs." However, the major problems facing the Project, such as the development of the biology and organic instruments, were only modestly affected by the PP requirement, compared to the difficulty of developing the new technology required. "This is where it's a little muddy in terms of what drove it, contamination prevention—being sure the materials would not produce contaminants when heated--or PP." The vendors certainly didn't understand that problem, so we had to control it very carefully. That's one of the reasons we had to insist on and get approved parts and materials, and this experience illustrates why these kinds of things need to be established and understood up front.

We did the parts and the materials management job very well, although we probably could have put more emphasis on systems engineering earlier than we did. The materials issue was a source of difficulty in the development of the computer, for example, No one understood what the impact of sterilization would be on it until we really got into it. When the subcontractor began changing materials to accommodate the heat requirement, they didn't really understand the computer well enough to assess the impact the materials changes would have; some of the new materials selected for their heat compatibility didn't work well, synergistically, in the computer. So we just kind of stumbled along like that for quite awhile, and something like 24 materials were changed in the process.

We used a number of new and sometimes controversial management approaches to solving our problems. Following the big reorganization early in the program, we set up the major components and subsystems essentially as "subprojects," each with its own dedicated technical functions. We also began to address the more serious problems by sending resident teams out to work with the subcontractors. Among other things, we had to change attitudes about how people identified and worked on problems in order to keep them visible, and we had to give the right people a reasonable chance to solve those problems. Such problems are inevitable, and it is important to make people understand that hiding them or underestimating them is the wrong way to manage them.

We made a strong effort to identify problems in a way that made it possible for people across the program to understand what was going on and how it might affect their own work. Above all else, people had to talk to each other. Jim Martin and I shared a common belief in encouraging thorough and open communication. The "top ten problems' issue was one of the mechanisms the Project office used to make people think about problems constructively, but they were so global in nature that they seemed to last forever. That was a little discouraging, and "I had to remind our people that there were a lot of other problems" we needed to concentrate on.

The lander camera PSA (photo sensor array) is perhaps the best example of a component that wasn't making it, and it eventually had to be resolved through our own management (Martin Marietta). The PSA was 'heat sensitive, and the subcontractor was dragging in his heels on doing the kinds of things that had to be done to properly test and develop it. So a management decision was made to bring it back in house and develop it in Denver. Meanwhile, a down-graded (compromised) alternate

PSA was being worked on at Langley because the Project wasn't confident we could do it. We started the effort by getting our people together and spending an intense period of time--several days-- thrashing out the problems and making sure everyone knew exactly what their responsibility was in terms of solving the technical problems, As a result, we never had a problem with the various people or groups involved not understanding what everyone's responsibility was and what they were supposed to be doing; the PSA was successfully developed according to its original design, without compromise, and the flight PSA's worked perfectly on Mars. (Note: All four Viking lander cameras continued to operate perfectly up to the day each lander ceased operation. The Martin Marietta PSA's were used in cameras developed and built by Itek.)

The problems associated with the TRW-built biology instrument were largely a result of underestimating the miniaturization technology required to make it work and the degree of management visibility needed to give it proper technical emphasis. However, while the degree of miniaturization and system complexity required in the instrument package was responsible for much of the difficulty encountered in producing its components, it did involve some materials and parts that were sensitive to heat and required some changes. Because of the particularly crucial need for sterilizing the biology instrument, it was probably subjected to some of the most severe heat qualification and sterilization cycles of any major component on the spacecraft prior to the terminal sterilization cycle at the Cape.

In terms of how that rigorous qualification and acceptance program affected spacecraft reliability as a whole, we probably could have achieved the reliability success we did without the PP requirement as a driver. Realistically, however, it wasn't as probable; so one could make a case (although we never attempted to quantify it) for the fact that it may very well have been the extra attention we focused on parts and materials--because of the heat requirement--that got us a superior spacecraft from a reliability standpoint. We "certainly fingerprinted the parts and materials much stronger" than we would have otherwise.

Richard G. Adamson. Every single part was qualified. First we made a matrix of part requirements and then went through a parts screening and selection process to get the biggest range in part capability, we could for qualifying against the requirements. This is essentially how we' put together our preferred parts and materials lists and inventories that worked so well for us throughout the program. "What that did, besides making the parts in which we had confidence readily available, was give us the opportunity to have the engineers spend more time on the design integrity of the system rather than on finding, reviewing, and selecting parts as they needed them." So, in that sense, there were actually "hidden cost reduction benefits" in doing it this way, aside from the management quality it afforded. It also afforded a much more efficient test program for parts that, based on today's technology, could operate much better and avoid the rework effort we experienced.

It's probable that the best lessons learned associated with PP may in fact be in how the preferred parts lists were set up and managed. "When a program can afford to inventory, the use of mandatory parts and materials lists would still be the right thing to do." Unfortunately, it isn't feasible for small programs because the minimal parts requirements don't justify it. But for a large program, the qualified materials and parts could be catalogued so that the program would have a ready reference of "hirel" (high reliability) parts; these are the kinds of parts that normally spell high cost but don't have to when they're properly acquired. Other important cases to study would be how components were ultimately managed in order to resolve problems that may have been, at least in part, a result of the PP heat requirement or the test programs created to test both the parts and then the boards or components to assure their heat qualification. It should be noted, in summary, that the imposition of these disciplines proved so successful in a number of ways that they may well have: (1) produced cost reduction benefits, (2) improved the reliability margin of the spacecraft systems, and (3) enhanced the working relationship between the elements of the Project--the Viking Project Office at Langley, Martin Marietta, and our subcontractors.

Harrison "Hatch" Wroton. PP certainly had an effect on the design and the manufacturing processes associated with all of the science instruments. The selection of materials and parts were as much a concern for the science instruments as for the rest of the spacecraft, with out-gassing being of particular significance. It also had an effect on decisions late in the program which sometimes caused equipment to be recycled. Recycling was a very complicated process; e.g., if a component had cycled all the way up through component-level sterilization, and we then found a problem on another article which suggested a similar problem on the sterilized component, "you would like to go in and look at that unit and see if you had the problem in it; sterilization, more than anything else, kept you from doing it, because you were looking at maybe a month long process to get it back into a ready (sterilized) condition again." So recycling involved a complicated sequence of things that made work on the biology instrument--which was such a complicated device anyway-doubly difficult.

Biology, of course, had its own requirement for sterilization which was more severe than the requirement imposed by PP, so that took some of the edge off of the PP requirement by itself. For that reason only, one cannot say that PP had a significant impact on the biology instrument. However, one must note that the biology requirement did spill over into the PP requirement imposed on other science and spacecraft systems, perhaps increasing that requirement where it might not otherwise have been necessary. In that sense, then, the effort to decontaminate the biology instrument had a greater impact than what might be suggested when thinking only about the instrument itself. We knew we were going to have to sterilize that instrument no matter what, so the terminal sterilization of the spacecraft was not a serious issue. However, if you think about "how would we have searched for life, having the biology and the mass spec aboard pretty much set our requirement for sterilization.' On the other hand, it wasn't so much PP as it was spacecraft protection, principally as a result of the biology and organic investigations. Even if organisms on the spacecraft itself couldn't contaminate the planet, they could still contaminate the sample path or the instruments and, thereby, corrupt the exobiology investigation. These kinds of things pretty well set one's requirements, and it's hard to imagine it being done any other way.

We reorganized the science program into an integrated project late in 1971, which essentially had all of its own support functions; we could not have succeeded without that kind of organizational autonomy. The way we did that for science essentially served as the model for the rest of the program once reorganization across the board became appropriate. Biology itself "became a 'super project' as of December '73. At that point, I spent most of my time at TRW in Redondo Beach" as resident manager until the instruments were finally completed. "Major development subcontracts do not run themselves; you've got to put a lot of effort into them. You need integrated management because you can't be negotiating everything that needs to be decided.' Once we developed the integrated function, the only things that had to be worked back through the program were those things that had an impact on the project, such as an interface chance or a ground rule impact (such as those involving the preferred parts or materials lists).

PP was just another part of the requirement, so it was not an issue in terms of 'should we be doing it or should we not be doing it, I don't perceive that it cost us on Viking a whole lot.' We had to have clean sample paths, such that the requirement would have existed with or without PP. 'It forced us into an extremely tight discipline on parts, on sterilization, on software, all sorts of things; we seemed to be learning over and over and over, and we're still learning it today, that discipline intelligently applied pays off tremendously."

3.3.2 Interview Summaries: Engineering

3.3.2.1 Israel Taback, Technical Consultant and Chief Engineer, The Bionetics Corporation

Supplemented by (1) Charlie King and (2) Ansel Butterfield, The Bionetics Corporation.

Israel Taback was the Viking Project Technical Deputy and Chief Engineer at the NASA/Langley Research Center. He was directly involved in all Project decisions regarding PP and contamination control, including the selection of sterilizable parts, vehicle design trades, and flight spacecraft trajectory selection. He served as chairman of the Viking Configuration Control Board which was responsible for approving the analyses and systems trades associated with the

Viking landers. He also participated in the Voyager-Mars study work that served as a precursor for the Viking Project.

The most significant impact of the PP requirement was imposed by heat sterilization on the Viking lander systems, and it was experienced most clearly in the selection of materials, parts, and processes. In the GCMS (Gas Chromatograph Mass Spectrometer), for example, we had some requirements on insulation and chemical compounds that were difficult to resolve. Out-gassing was something of a problem for some of the materials we used. However, when we talk about the potential for contamination in the exobiology instruments, the outgassing issue was more a matter of controlling biota particulates, spores, etc. There also were some problems with some metallic materials, e.g., some of the screens in either or both of the exobiology instruments contained a nickel compound that was getting into the instrument. In any case, because these kinds of things were happening to us, we had to change a number of the materials used in fabrication. So the severity of the requirement tended to drive a very intense selection and qualification procedure as well as the development of new ways to test and assure the integrity of the selections.

When we started Viking, we were still considering chemical sterilization (ETO, ethylene oxide). Heat, on the other hand, "was a clean and relatively painless solution that produced no overpowering problems beyond those associated with the essential challenge of building components capable of surviving the qualification testing and the sterilization temperature." However, while the Viking experience is an excellent subject to examine and evaluate when planning future missions, today's state-of-the-art materials and electronics technologies are sufficiently advanced and different from those used on Viking to require additional study to be sure they can be heated to meet the PP requirement.

Although other methods of cleaning and sterilizing spacecraft systems were studied and evaluated, dry-heat sterilization was by far the best choice and should continue to be in the future. We did pay for it in weight and performance, however, in that we had to have contamination control covers and barriers. Anybody who has to worry about keeping a spacecraft within a PP policy rule will also probably have to find a way to keep it in a biologically secure container that must then be opened in space. The lander had to have a shell around it (the bioshield); and once it was sealed in that shell for sterilization, it couldn't be taken out without contaminating it and forcing a sterilization recycle. Fortunately, that proved unnecessary. While heat Sterilization itself is not overly expensive as a process, the unique technology reflected in those features and components required by whole-system, biologically sealed spacecraft (such as the bioshield) account for extra cost. But it is also possible that the procedures and disciplines imposed to cope with PP-related requirements--such as the mandatory parts lists and the extra attention we focused on ensuring the qualification and reliability of the materials and parts we selected--may ultimately have produced modest cost-reduction benefits as an offset.

Once we dropped the qualification temperature on parts down to around 1292, we had much less of a technical problem meeting the PP requirement. "Someone did a nice time/temperature trade" and lowered the temperature to a level that proved more reasonable for testing components. The important point is that "the PQ requirement never really changed; the 1×10^5 chance of planetary contamination for up to 50 years, whatever it was, I don't believe was ever relieved as far as Viking was concerned." We simply made the heat exposure time longer in order to lower the temperature but achieve the same result. "So the method of getting there was changed, but not the requirement." There were a number of studies done concerning the effects of time/temperature trades and die-offs (of microbial populations) to help us do that without compromising the sterilization and contamination control constraints.

One of the principal lessons learned is that "if you change processes or materials, watch out for the consequences." The. PP- requirement isn't the only reason you make such changes, so that should be a fundamental rule, but the Viking heat specifications were certainly high enough to make a number of those changes necessary. However, modern electronics and circuit boards should no longer be a problem because they are now more typically designed to higher heat tolerances. Many of the unique problems have been resolved as well. The Viking decelerator (parachute), for example, was packed so tight that it could not be sterilized by the terminal sterilization heat soak; we solved the problem by sterilizing it independently. There were also some materials problems associated with the heat compatibility of both the fabric and some dyes used in making the parachute that had to be resolved.

The preferred or mandatory parts list was the single most outstanding management tool.

Anyone who needed parts was required to use parts qualified for that list and out of existing stocks. Exceptions were allowed only on a case-by-case basis, and even then the selection was controlled by the Project. That meant that we already had most of the parts, materials, and chemicals that we were likely to have to worry about. "It was tough going in because you had to have qualified parts of various kinds, and you had to have a certain amount of paperwork for people who wanted exceptions.' I'm really not sure which led which, whether it was the mandatory parts list developed at Martin Marietta and JPL or the PP requirement itself, but it was the biggest factor in influencing us to go to a restricted inventory of the kinds of parts we needed for the overall program. It makes good business sense whether or not you have PP to worry about.

As far as the heat sterilization decision is concerned, heat is still the most attractive method. It's easy to do, and we wouldn't have to learn anything new. Heat is hard to beat because you can do it within the acceptable range of all the components you're likely to use; the other methods involve potential unknown degrees of risk for those components and might require new technologies that carry their own burden of compromise. There are other unknowns to consider as well, such as the new computer technologies which reflect significant advances compared to what we used and had such a difficult time getting to work for us. These kinds of things will have to be studied closely in perspective with the requirement for thermal sterilization. But there is no reason to depart from heat or to believe .that we can't do it this way with the new technologies as well as we did if with Viking. As long as there is an outside chance for biological interest in Mars, the need for sterilization is probably going to remain I necessary.

We learned enough from Viking to know that we can probably clean up and sterilize a spacecraft and its instruments well enough for future missions without getting into new problems. There are, however, a new breed of electronic sensors that are extremely sensitive and would be desirable for those missions, and we probably need to learn whether their temperature sensitivity is any greater or less than what we used. "If the new materials don't have a thermal problem, then it seems to me the only new problem is: how do you go get a [Mars] sample without dirtying it [the spacecraft return system] up, and then put it into a container so you don't have to worry about contamination until you get it back to a chamber where you can handle it." And we always need to remember that "it's a systems problem, not a parts problem. Putting it [PP policy] at the front end of a program is an absolute necessity.

Charlie King and Ansel Butterfield. Parts, materials, and processes represent the most critical area of impact with respect to heat Sterilization. For example, the selection of material to make electronic circuit boards had to be determined on the basis of heat compatibility to ensure their stability. In some of the electronic components, we had to use thermal-tolerant resistors which had some unique characteristics as far as how they could be used within the circuitry. Solders and potting compounds were also affected by heat, and in some cases it proved difficult to find alternate materials that worked well. Solders could become brittle and crack, as one example. Conformal coatings were a problem because they were often applied too thick; the coating would expand when heated and stretch the parts until the parts failed. One of the tough challenges, then, was to standardize how to mount parts. For example, we had to standardize part preparation and cleaning for soldering, and we had to establish conformal coatings and their thicknesses.

Some materials were rejected because they outgassed badly and produced organic contamination: the organics would then condense on a cooler surface, and that was a special problem in some of the components. Moreover, there were problems with metal parts as well, in that as metals relaxed or expanded and contracted, things like creep relaxation caused fasteners like nuts and bolts to loosen or screws to unthread. Rates of heating also had an influence, in that the thermal inertia of how efficiently heat soaked into the spacecraft during terminal sterilization determined how long the lander capsule had to be sterilized. Its coldest point had to get warm enough for a sufficient period of time to ensure sterilization, but the parachute material was packed so tightly that, once packed, it heated too slowly and could not be heated adequately to achieve sterilization. As a result, it had to be sterilized by itself before packing, and then terminal sterilization essentially finished the job by sterilizing the exterior of the decelerator (parachute) canister.

There were a number of unique component problems associated with the sterilization issue. One of them involved the selection of the fluid used in the gyroscopes, which was driven very much by the Sterilization requirement. The heat-compatible fluid had to be quite heavy to float the gimbals, and it didn't flow well through the orifices. It was a very difficult problem to solve. The GCMS problem was another unique matter because it was at first being developed independently by JPL and didn't have to comply with Martin Marietta's mandatory parts list (it was later developed as a separate NASA program). It was, therefore, originally full of resistors that were not stable and suffered voltage shifts. The implications of sterilization were not well accepted by the GCMS program then or later, which made it difficult to qualify it for the heat environment; it contained some particularly sensitive electronics in which corona was a possibility if the potting compounds used failed, and heat-tolerant potting compounds were difficult to find.

Sterilization did have an impact on propulsion, as well. It reduced the options in terms of what kind of propulsive fuel would be used. Then, once hydrazine was selected-partly on the basis of its toxicity for microorganisms--it was further processed to reduce the probability for its own microbial population even more. There was some work done as well to be certain that the chemistry of the exhaust plume would not contaminate the sample field, and the engine nozzles themselves were extensively redesigned to minimize the site modification influence of the exhaust plumes. The fuel was the only flight component put into the spacecraft following terminal sterilization, so a fueling capability had to be developed that would not allow contamination to enter the capsule; there had to be good certainty that the fuel itself was sterile.

3.3.2.2 John D. Goodlette, Vice President and Chief Engineer for Space Systems at Martin Marietta's Space Systems Group, Denver, CO

John Goodlette began his Viking responsibilities at the pre-proposal stage roughly two years before the request for proposal was received. He served as the system engineer for the lander/orbiter integration role, as well as the lander design role, and was later named Technical Deputy to Walt Lowrie as a counterpart to Israel Taback, Technical Deputy to the Project Manager at NASA/LaRC's Viking Project Office. He served in that capacity throughout the rest of the development and test program in Denver and the launch program at KSC, and his work included studies associated with PP technology decisions. During mission operations at JPL, he served as Viking Chief Engineer.

PP was viewed only as one of many technical engineering specifications associated with spacecraft systems design. The challenge was to put a clean and sterile spacecraft on the surface of Mars that would allow biological and organic chemistry experiments to be conducted "with a high probability for producing uncontaminated and reliable data from near-pristine surface samples.' To do so, a sterilization procedure had to be developed that could provide secure, reliable results for the entire lander capsule (all of the elements and components that made up the descent capsule). This could most efficiently be accomplished by sterilizing the assembled spacecraft in a closed environment (a sealed, bioiogical-barrier envelope, the bioshield) so that the integrity of the procedure could be maintained until the flight spacecraft was safely in space. Heat was believed to 5e the best and most predictable sterilization environment for this purpose.

In spite of the fact that a decision had not actually been made to commit to using whole spacecraft dry-heat sterilization at the time of the proposal submittal in 1968, there was no data to suggest that gas (ethylene oxide) sterilization could meet the requirement with any kind of success margin or technical advantage. However, it became clear during the latter stages of this phase that a significant test-program would be necessary in association with heat sterilization earlier than would be possible for the complete spacecraft, to assure compliance with the PP requirement and the technical impact that would result from the use of heat.

Even before the Viking request for proposal was received, the Martin Marietta team had done a fair amount of sterilization research at the component level, such that the extent of the problem was already partially understood. In addition, some selection options were already being defined. It became clear at that point, for example, that many relatively common non-metallic materials used in a variety of electronic components, e.g., circuit boards and certain kinds of' discrete parts, simply wouldn't stand up to the heat environment imposed by the Sterilization procedure. Coatings, adhesives, and rubber-like parts (like O-rings, gaskets or other kinds of seals) were a serious problem; and numerous new materials were required to replace those that couldn't qualify for the heat environment. In addition, some of the materials used in electronic components, such as capacitors, could explode or become quite vulnerable to damage during the application of sterilization heat.

Metallic components of differing properties sometimes failed to work with the integrity expected of them when used together, producing creep and other problems associated with metals that react to heat at different rates. In the case of creep, attachment fasteners--such as screws of different composition from that into which they were threaded--would loosen and back out. Specifications for some of these parts, such as those establishing standards for elongation allowances, had to be modified to reflect that the parts would be heated. In fact, the amount of heat-induced elongation had to be well understood so that it was known what the effect of Sterilization would be in very precise terms.

However, while some metallic materials were selected as alternatives to the original design choices to afford more reliable performance in association with the PP heat environment, most of the changes were of non-metallic materials. Good examples of system components that were particularly sensitive because of their extensive use of non-metallic materials include the bioshield, the batteries, and the parachute. The general policy for Viking was that everything designed to enter the martian atmosphere (biosphere), everything associated with the lander or its descent to the surface, had to be sterilized first at the component level and again at the system level.

Component-level sterilization was particularly critical in the case of the parachute, which was a special problem because it was packed so tightly in its canister that it couldn't be assured of achieving the optimum temperature during the terminal sterilization heat soak; after being sterilized and essentially sealed at the component level, terminal sterilization wasn't really required. The system level (whole spacecraft) terminal sterilization cycle was, therefore, directed more at the external parts and surfaces of the decelerator parachute canister rather than the parachute itself.

The bioshield fabric had to seal reliably to maintain a positive internal pressure (pressurized with nitrogen gas during the heat soak) as an additional barrier against recontamination following terminal sterilization. The bioshield also had to have electrical conducting wires woven into it to help carry away static electricity. The batteries represented several related problems that were particularly difficult to resolve. The separators were hard to develop because of their sensitivity to heat; it was necessary to be careful about the charge state of the batteries at the time of sterilization and about the volume of the electrolyte which would expand as it heated. While they were difficult to develop, "the tough specifications applied to the batteries appear to have produced extremely good Viking batteries."

PP provided surprises by producing problems that weren't expected. For example, the problem in developing good heat-tolerant batteries was expected to be difficult because batteries are known to be sensitive to heat. On the other hand, the problems experienced with the computer and its memory were a surprise. Many problems were not directly or significantly due to PP. The biology instrument was expected to be very difficult, and its actual difficulty exceeded anything anticipated for it. However, while its problems were in fact enlarged by--though not necessarily produced as a result of—the sterilization requirement, one must remember that the very nature of the biology instrument demanded severe sterilization; solving for PP in the biology instrument was only a small part of the challenge undertaken to design and build it.

An important point to make at this stage is that Martin Marietta and JPL were the only organizations leading serious work on heat qualification associated with spacecraft parts and materials, "We were writing the book, and essentially writing it as we went.# To help improve our understanding, we began early to build prototype packages for some of the subsystems. It was during this kind of activity, for example, that the creep problem was encountered, and it was unanticipated because creep is generally associated with much higher temperatures than those imposed by the Viking test and sterilization procedures. It was, instead, discovered that creep can be a problem even at lower temperatures.

The selection of parts, materials, and processes used to fabricate the spacecraft systems was heavily influenced by the fabrication methods employed. Many of the prior fabrication and test methods couldn't be applied in the case of Viking because of sterilization and that had to be understood at the start. That is, design standards had to be established for preferred parts, materials, and processes that could withstand the heat environment imposed by sterilization. When it was necessary to depart from the preferred parts and materials lists to acquire unique items, it was necessary to verify that the special items met the same standards. These standards affected how both the system-level and box-level testing was done. Test methods had to be employed that could test subsystems and components without the need to take them apart; once a component box was fully assembled, for example, it had to be tested in such a way that its integrity could be assured without disassembly. The same was true in the case of terminal sterilization in that the test systems had to be built into the spacecraft subsystem to facilitate complete post-sterilization testing without disassembly; at that stage, any disassembly clearly would have voided the sterilization procedure.

A number of things resulted from this discipline and the methods it drove which may have produced some cost benefits. So much repetitive testing was required that automated test programs were designed which saved a great deal of time and produced great precision in the repetitive nature of the tests conducted in this manner. On the other hand, this method produced a great deal of data to examine, so a lesson learned might be that automated testing seems to require automation in affording verification of the data as well as the repeatability against predefined standards. The test program itself made it possible to develop a preferred parts list and inventory of those parts that were qualified and could be supplied to subcontractors as they needed them. Not all of the parts could be provided in this manner, but the vast majority could be--and produced significant savings and efficiencies. The decision to become a central clearing house for qualified parts that could then be provided to the subcontractors and vendors supporting the prime contract was both a unique and highly beneficial concept. It afforded the ability to handle a large 'dollar volume" of parts and materials at a better price.

A conscious decision had been made not to push technology where it wasn't necessary. The only considerations that could affect this policy were: could we meet the weight requirement with it, and could we heat-sterilize it. In these situations, we didn't redesign significantly but simply adapted the technology to the PP requirement. Many systems got through the PP gate quite easily, simply because they normally had to operate in a thermal environment anyway and did not have to be modified. However, magnetic media in particular were a unique problem in two cases, because the magnetic properties of coated memory media tend to change with the application of heat.

One of these was the tape media used in the data storage tape recorder, which had to be a metallic tape to achieve heat tolerance. The computer represented the second of these problems, principally because it utilized a densely packed, plated-wire memory only two thousandths of an inch in diameter and was, therefore, easily affected by heat. However, the mission requirement itself, due to the anticipated operating temperature range on Mars, was the major environmental factor in the computer memory problem; it caused some design changes in the computer's ability to recognize the temperature-dependence factor and employ temperature-compensation devices. The static memory planned for the computer had to be reduced to accommodate the additional circuitry.

The management system employed to get the Viking program and many of its problems under control may not have been driven directly by PP, but PP certainly helped to emphasize areas in which related issues were clearly defined. Because some of the major engineering challenges underlying many of the program's major issues were a product of PP, whether driven by COSPAR/NASA policy or contamination control requirements, it could be said that PP was at least part of the driver for the management style employed. The organization was very deep and narrow before the reorganization management system was implemented, such that communication was very difficult. The new system, however, was relatively broad and shallow, such that it reduced the number of horizontal levels and, consequently, the number of authority conflicts, allowing a broader and more efficient span of control.

Mission Success was an organization which brought together in one group the engineering, reliability, quality assurance, etc. disciplines necessary to focus on any given problem, define it, resolve it, and follow through on corrective action in a timely and efficient manner. Mission Success was partially associated with the tight control over parts and materials and accomplished the same thing for problem visibility at the scale of the program that concepts like the preferred parts list did at the piece-part level. This composite of highly productive program activities was directed superbly by Don Hobbs, and he seemed to have a unique talent for it. Mission Success was an on-going process, in that it provided a visible track record or audit trail for every problem identified on the program, and was maintained religiously in a central control room that allowed everyone to review what was happening elsewhere on the program relative to their own' activity. In this way everyone could find out what was happening and when. Mission Success was itself a lessons learned application process that preceded PP but served as an ideal vehicle for exposing and revealing the parts and materials factors that affected higher levels of program activity.

Subcontractor and vendor management was something of a problem as well, in that they had to learn new ways of dealing with Viking-peculiar requirements and procedures. Some of the subcontractors did not understand or act to meet the thermal specifications imposed by the PP requirement or the sterilization specifications, and action had to be taken to overcome such problems by either providing direct resident management or by changing subcontractors. An example of the latter case was the lander camera PSA (photo sensor array). The subcontractor essentially refused to acknowledge the heat requirement and perform the necessary thermal analysis it mandated and was ultimately removed from the list of suppliers.

The PSA, in fact, was taken back in house at Martin Marietta and ultimately produced to its original design specifications with complete success-even though the Viking Project Office doubted Martin Marietta's ability to do so and had started designing a simpler PSA with less performance range. It should be noted that the PSA proved to be very sensitive to sterilization heat. (Note: the lander cameras equipped with the Martin Marietta PSA's were built by Itek; all four cameras performed without failure or malfunction throughout the lives of their respective lander systems, providing thousands of images of both Mars landing sites in low and high resolution, two near-infrared wavelengths, and tri-imaged color.)

Everything one can do as early as possible, to state requirements to the suppliers, vendors, and subcontractors, is going to make the program work much better from the start. If there is a lesson learned in this activity, it's that the prime contractor and project management must do its best to first understand the major factors that drive and set the standards, and then must be sure that the suppliers and vendors understand those requirements as soon as possible. The same thing can be said for providing technical specifications for manufacturing processes and fabrication plans. Moreover, anytime there is a major development contract like that used in association with the biology instrument or the computer, the prime contractor should plan on having a technical team in residence from the very beginning. Even when the subcontract involves relatively routine work, there should still be people at the program level to closely monitor and react to what is happening at the subcontractor's operation level.

3.3.3 Interview Summaries: Research

3.3.3.1 Dr. Joseph A. Stern, The Bionetics Corporation

Supplemented by ('I) Alan R. Hoffman, JPL; and (2) Norman D. Fields, Microbiologist, The Bionetics Corporation, Kennedy Space Center.

Dr. Joseph Stern, President and CEO of The Bionetics Corporation, Hampton, Virginia, was the manager of planetary quarantine and organic contamination control support in a subcontractor role for the, Viking Project Office at NASA/LaRC. He also coordinated all related activities with the system prime contractor, Martin Marietta Corporation (Denver), aiding them significantly in making the decision favoring dry-heat sterilization. He served on various working groups and NASA-coordinating committees to assure compliance with PP policy.

Some of the most interesting and productive pre-Viking PP work was done during the precursory period prior to the Viking proposal effort (mid- and late 1960's). It was during this period that a number of the methodologies proposed for sterilization were researched very seriously for the first time (relative to planetary spacecraft systems), although this work was as much a facility-development effort as one of determining the best course to follow for sterilization. Chambers were built to conduct both heat and ethylene oxide (ETO) modes, but it was found that ethylene oxide was too hazardous and corrosive. "There was a facility built at JPL at that point in time to establish a test operation, and it was called SADL--Sterilization Assembly Development Laboratory.' It was a full high-bay area that included an ET0 chamber, and we eventually managed and used it as part of our research program. Its primary section was really just a very clean assembly facility, after which major subsystems or entire spacecraft could be moved out through several different kinds of sterilization chambers, including ET0 or heat.

Other sterilization methods also were evaluated, however, including radiation (primarily gamma-ray). One of the sterilization facilities considered by NASA/LaRC was MAST (Model Assembly Sterilizer for Testing), But, while MAST was generally an innovative and successful technology in terms of facility design and control function, it was quite complicated and costly to develop. MAST was based essentially an heat sterilization of an open spacecraft, after which component-level assembly work on the spacecraft was conducted in a large, ultra-clean chamber that could be occupied by technicians in biological isolation suits (BISS). .Components that couldn't be heat sterilized were conveyed into the main chamber through either a primary antechamber or smaller pass-throughs in which other types of component-level sterilization could be done (e.g., swabbing, ETG). The MAST program ended early due to its complexity, and most of the effort soon concentrated-on identifying problems and solutions associated with whole spacecraft, dry-heat sterilization,

"The planetary quarantine requirement, which is the COSPAR requirement, was pretty well overwhelmed by the requirement that the biologists put upon the Project" by making the probability so low that there could be virtually no chance that their experiments would detect spacecraft-borne biological or organic contaminants that could corrupt their investigations. The PP and contamination control research program was very thorough: "we had to convince the engineering and quasi-scientific community of the logarithmic relationship between numbers of organisms' and temperature and time [probability for the destruction of microorganisms when heated], and that there is no such thing as an absolute death of a population--you just reduce the probability to something that is acceptable.' The essential knowledge that came out of the work was and is very sound, and it affords a solid foundation that is as trustworthy and applicable for future programs as it proved to be for Viking. It also helped to demonstrate the importance of maintaining active review evaluations with respect to sterilizable parts due to the rapidly evolving nature of the materials and technologies associated with them.

"The original specification for heat sterilization of a spacecraft, and also for parts and materials, was written at JPL.' The IO-degree safety factor specified at that time was in centigrade rather than Fahrenheit, so that each time the factor was applied it produced an 1 &degree increase in Fahrenheit. At that point, the proof-test temperature was to be 145% and the assembly sterilization temperature was 125%; thus, the application of the safety factor brought the component sterilization temperature to 135C and the proof-test temperature to 155C. That meant that parts had to qualify for a 135C (275F) component sterilization at 155C (31 1F). "The thing had gotten just way out of scope, and it created tremendous hardships for the parts and materials people." The high temperatures were also a problem for the GCMS, because some of the heated materials could outgas organic contaminants.

"Our objective, when we started supporting Leo (Daspit, LaRC-VPO), was to work as hard as we could to reduce the planetary quarantine constraint." That is, if they were working toward 725'C hardware, "we'd like to sterilize down at 11 5C and relieve the proof-test down at 125'C. The purpose was to reduce the strain that the hardware would have to take and to build greater reliability into it; it was eventually accomplished by making some carefully calculated trades--lower temperature for greater time.

One lesson learned is that it doesn't necessarily pay to develop parts lists for sterilizable parts unless it is a very active, current, and constantly updated program. This was done at JPL, where a parts list were developed to reflect parts that could withstand ETO, heat, or a combination of both; but no attempt was made to keep the list updated. By the time Viking needed those parts, the parts list was outdated and useless: the parts were outmoded and represented old technology. The selenium rectifier problem, for example, was a result of this; moisture in the rectifiers expanded and caused them to blow up when they were heated. 'So going into research programs to develop parts and materials in advance of a project, needs to be a far-sighted program that looks at what kinds of parts and materials you'll be using three to five years downstream when you build the hardware (rather than the parts available at the time of the research)." The sooner the requirement is recognized and accepted, and "you stop fighting it,' the sooner you can do whatever has to be done to meet it. The amount of lead time afforded in this process is very important to both the planning of a project and the success or difficulty its development program will ultimately experience.

We may now have the technical capability to build extremely clean spacecraft without sterilization; but, if a spacecraft is carrying life detection instruments, sterilization again becomes a very probable requirement. There simply isn't any other way to clean up an entire spacecraft, biologically, to assure the low probabilities of contamination required by those kinds of instruments. And, because of the quality parts and the tighter controls associated with such procedures, it is reasonable to propose a Viking-like PP requirement as a technical standard regardless of whether PP policy must be satisfied.

Alan Hoffman (JPL). What we were mostly looking at during the period leading up to Viking (mid- to late 1960's) was the calculation process associated with how one determines what kind of sterilization cycle should be imposed on the spacecraft. We had to monitor the microbial burden on and within the hardware and make the measurements we needed to understand that issue and, then, based on that, determine the extent of sterilization that needed to be performed to kill or at least reduce to some satisfactory statistical minimum the organism population.

As far as the debate over whether sterilization was really needed or not, there was a certain amount of uncertainty on both sides of the argument. 'I felt that, from an engineering standpoint, we really had to do the best job we could and convince ourselves analytically, and from what we actually exposed the hardware to, that we would not--even under the conservative assumptions that Josh Lederberg and Carl Sagan were advocating at the time--contaminate the planet or the biology experiments."

One of the key factors involved in the assessment to determine how best to sterilize a spacecraft is the Probability of Growth (PJ parameter. The original assumption was that the P, was $1x10^{-4}$ for Viking, and that had 'an impact on the duration of the sterilization cycle. A couple of key aspects of establishing the requirements and then implementing them are: (1) you have to have agreement on the Probability of Growth factor established by the international science community so that you can then look at your options, given the P,, for how best to avoid contaminating. the planet and then (2) you must choose the method you need to reduce the microbial load on the spacecraft to the desired level, which for Viking was dry-heat sterilization. That determination was supported by the fact that ET0 worked best as a surface treatment, for the most part, and would have been much more difficult and uncertain-not to mention risky--to use. If you got your coldest points in the spacecraft up to sterilization temperature using nothing but dry-heat (in an inert gas like nitrogen), heat does indeed kill microorganisms effectively, consistently, and predictably.

"Once you make that decision, you then have to establish the requirements on your piece parts, fabrication processes, and for the whole selection process.' The designer has to know these things up front, relative to his part needs; then, early on, you have to procure and evaluate parts that can survive. "One of the key things that we've learned here [JPL] over the years, as far as spacecraft are concerned and which applied to the Viking landers as well as to the orbiters, is that you must have good parts, simple block redundancy, and a good test program." The fundamental requirement is that parts must be subjected to the heat environment for qualification, and it should be noted that the heat environment must be viewed in the same perspective as all the other qualification environments--launch environment, vacuum of space, vibration, thermal, radiation, etc.

There was, early on in the Viking program, some research into the high-temperature performance of materials, with sterilization specifically in mind. There probably should be an on-going program of some kind to do this kind of work in order to stay current with state-of-the-art materials that would be compatible with the heat sterilization environment. However, this kind of research should not only identify neat-compatible individual materials, it should also determine how such materials might react synergistically with each other in that environment. We ran into some materials synergism problems on Galileo, for example, in that there were some interactions with the environment that were unanticipated. For example, "if you do an evaluation of one material by itself and the other material by itself, they may be fine; but when you put them together in a temperature and UV environment, they may have a tendency to interact and degrade performance." Some of the earliest heat-sterilization tests revealed quite visibly some of the changes that occurred; and, while not unanticipated, they at least suggested that there might be some other interactions and changes that were not visible. Closely related to that problem is the potential difficulty with using a variety of materials for specialized purposes, such as cable insulation, connectors, potting compounds, etc., in localized areas and in very close proximity.

We knew from the outset that we would be sterilizing the lander, and the whole process was then geared to adequately account for that sterilization activity. So it wasn't one of those situations where you have an already designed spacecraft upon which you're imposing this very stringent requirement; the requirement existed first. Therefore, the lesson learned is to establish the need and the requirements as early as possible. These kinds of environments have always been considered, but one has to worry about "single-event upsets" when it's time to select and use alternative parts. We didn't have to worry about many of these situations on Viking, for the most part, because the selection decisions had already been made on the basis of the right criteria at the very start. .It's also important to maintain constant interaction with the cognizant engineers who are supplying the hardware early on, making sure they understand that the heat requirement is a critical requirement and that it is not going to go away.

This is where the preferred parts and preferred materials lists were very important, as well as the thermal analysis models used to test everything again and again as it evolved through the fabrication process--becoming circuit boards, small components, complete instruments or subsystems, and finally the major spacecraft elements. It's important to start detailed thermal analysis at a very low level. Reliable qualification of materials and piece parts is very important to packaging design, because it is in the packaging of electronics, for example, !hat the quality, reliability, and knowledge of these items become critical. The later problems arise in this process, the more difficult they are to resolve. It's not an easy analysis to do, especially early on when detailed designs--like board layouts--don't yet exist.

As spacecraft get larger or become more complicated, in terms of the number of large, virtually autonomous subelements, such as independent lander/rover systems, one option we might consider is sterilizing in modular sections. Although component level sterilization was considered and pretty much rejected during the pre-Viking research period, in programs like MAST/BISS (reference, J. Stern, this section), the sire and complexity of future .spacecraft may drive us back to something like that. Major operational components of a spacecraft might be assembled in this manner, with each essentially final-assembled and sterilized independently first.

As one scenario, "you could sterilize it [in its modular sections] in the space station and then do an effective clean-room spacecraft assembly out in space." The detailed assembly-level subsystem testing could be done on the ground, subjecting parts and components to high-temperature qualification/reliability testing and then sterilizing and packaging them in biological envelopes of some kind to maintain their sterilization integrity. That would control the deep contamination burden inside the major spacecraft elements, and all you would then have to worry about up at the space station is doing "a little toasting" to get anything that may subsequently have contaminated the surface of the spacecraft components. The advantage of working in a naturally sterile space environment is that if anything went wrong in a component or subsystem during sterilization, it could be changed without fear of recontamination. It might also be possible to incorporate and utilize robotic final assembly at the space station: that would be a beneficial solution from the standpoint of preventing recontamination, because humans are natural biological contamination sources and make the problem of handling sterilized spacecraft components more difficult.

Norman D. Fields. We did the Viking pre-sterilization research at Kennedy Space Center to determine what the bioload might be in the various work areas where the spacecraft systems would be exposed prior to sterilization. The work was done during the period just prior to the start of the Viking contract work in 1968-69, before the major sterilization decisions had been made but when dry-heat was considered the most probable mode. Titanium strips were exposed in these areas for a period of time so that we could determine what kinds of bacteria were present and to find out if there might be some spores present that could survive the terminal sterilization cycle. The lab had a Viking heat sterilization simulator so that we could expose our samples to that cycle.

We inevitably did find a few spores that were capable of surviving the sterilization cycle, and a few were especially resistant to heat even over long periods of time. One in particular, which became widely known as super-spore, survived dry-heat sterilization for an extremely long period of time. It wasn't possible to increase the sterilization temperature because of the impact on electronics, but we did investigate the effect of humidity in conjunction with the hot, dry nitrogen used as the sterilization medium. Research elsewhere suggested that slight amounts of moisture increased the effectiveness of sterilization.

Once we got into the Viking program, most of the biological sampling plans were written by JPL and Martin Marietta. Our studies did find a number of opportunities for the introduction of microbial contaminants, such as in water baths used to determine the survival of spore-formers. So our own system, as it turned out, was vulnerable to introducing its own contamination, not unlike concerns associated with the biology experiments themselves; we had to take measures to ensure that our water was sterile to reduce the opportunity for our own procedures to contaminate our samples.

3.3.4 Interview Summaries: Science (Exobiology)

3.3.4.1 Dr. Gerald A. Soffen, Associate Director, Space & Earth Sciences, I\IASA/Goddard Space Flight Center, Greenbelt, MD

Supplemented by (1) Dr. Norman H. Horowitz and (2) Dr. Gilbert V. Levin.

Dr. Gerald Soffen was Viking Project Scientist in the NASA/LaRC Viking Project Office. With a background in biochemistry, he managed the development of biological instrumentation at JPL before taking on his Viking responsibilities. He chaired the Viking Science Steering Group, which represented approximately 70 scientists who had been selected for the various Viking science disciplines and teams (13). He then served in a liaison capacity between the science teams and the spacecraft development program, representing science interests and requirements,

Dr. Norman Horowitz is a Professor Emeritus of biology at California Institute of Technology and developed the pyrolytic release experiment for the Viking Lander Biology Instrument (VLBI). He had previously Seen an experimenter for the Mariner 6/7 missions and is eminently known for his classical work in Neurospora genetics. He is the author of To Utopia and Back: The Search for Life In the Solar System, 1986, which was based on the exobiology results of the Viking program.

Dr. Gilbert Levin, President of Biospherics, Inc., Beltsville, Maryland, developed and served as principal investigator for the labeled release experiment in the Viking biology instrument. Dr. Levin has an extensive background in microbiology associated with public health services and medical research. He was a long-time proponent for a Mars soft lander and developed a sample acquisition and analysis instrument called Gulliver for NASA for the conceptual Voyager-Mars program which led to Viking. He has authored or co-authored numerous papers on Mars exobiology topics, including (with J. M. Hall): Quarantine Concepts For a Mars Return Sample Mission, published by COSPAR, Life Science and Space Research, Vol. XV, 1977.

Dr. Soffen. The PP requirements set down for Viking produced one of their most important benefits very early. Before virtually anything else could be done to define and impose the requirements, the technology necessary to conduct the research had to be refined to a much higher state of reliability. That is, an entire technology associated with a special aspect of bacteriology had to be developed incorporating techniques and methods involved in such things as, for example, taking swabs to assay organisms/spores on a spacecraft surface or within its material make up. Moreover, assessing microbial populations is a very difficult task, and the business of testing the effectiveness of sterilization! essentially became a matter of statistical analysis.

There were two reasons driving the probable need for sterilization at the very start (1961). The first, clearly, was the protection of the planet from contamination by transported Earth organisms. The COSPAR perspective evolved out of the debate going on during that period about PP, particularly in the case of Mars. The second reason "was to be sure of whatever answer we got"; i.e., we had to assure ourselves that we did not contaminate our own experiment and be unable to understand or trust the integrity of what we learned with it. "In our various meetings, conversations, papers, and letters was the notion that you've got to protect Mars." The reason was really quite simple: "if you screw it up [contaminate Mars], you might never get the answer [you'd never know if life detected there was of Mars origin or had been carried there by a spacecraft from Earth." Any spacecraft carrying "bugs" (microorganisms) is very likely to contaminate its own biological investigation. That is, if we didn't take precautions, we might contaminate experiments (in the case of life detection instruments) and corrupt their results through the increased probability of detecting living organisms transported on the spacecraft.

At that point, the discussions were concerned only with living organisms and life detection, not with the non-living organic chemistry aspect of exobiology. There was talk about various ways of sterilizing hardware; dry heat, ethylene oxide, ultraviolet radiation for surfaces, and some techniques the didn't involve Sterilizing the whole spacecraft. Larry Hall had funding to support studies for looking at some of these things, but it was all-pretty new. The Army, particularly at Fort

Detrick, had already been looking at sterilization techniques like ethylene oxide and gamma radiation. However, "we were in a different ballgame because we were trying to kill not just large numbers of organisms, but trying to get down to the last one." That's very hard to do, and that was when the whole probability issue began. "People asked, what's the probability that you'll land an organism on Mars?" The problem tends to become one of statistical analysis at that point, in that one contaminant is as bad as many, so the effort was to get the sterilization survival probability down to the absolute minimum. Research dealt with population death curves for organisms exposed to sterilization procedures, time versus temperature, ex.; then the problem WBS "how do you how when the last organism is dead?" The fact is you can't. It was an intriguing, intellectual exercise, but in practical terms the best solution would have been to simply take precautions and do the best you could with the resources available.

Josh Lederberg and Carl Sagan were on the conservative side of the issue, wanting to maximize the sterilization success factor, while Norm Horowitz voiced the liberal side of the issue and wanted to be more practical by using common techniques--swabbing, use of gasses, etc.--practices more like we'd use in the field. He felt conditions on Mars were so extreme that organisms couldn't grow there even if they survived sterilization and transit. He believed we were treating Mars too much like the Earth, which wasn't realistic because the environment there was so severe that it wasn't necessary to take the kinds of precautions suggested by the conservative camp. The conservative view was, on the other hand, "hey, this is all unknown and you can't play with it; the consequences are so grave that you can't afford to take any risks."

COSPAR was nothing more than a meeting ground of people, and it didn't really have any views of its own. The agreements we [NASA] speak of as COSPAR PP requirements are really general consensus agreements between ourselves and the international science community, including the Russians; COSPAR itself didn't actually issue anything. Those early agreements simply resulted as a consensus from the discussions that were going on during that period, particularly between the United States and Russia: then NASA responded by essentially recognizing the conservative side of the argument in its own policies. The conventional way for people who are given responsibilities in an organization like NASA to respond is to protect their own territory, and it's certainly no different for the issue of PP. That is, there is a strong tendency to act like policemen by developing positions and policies that favor the more conservative point of view. For this reason, then, there really never was a recognized, serious consideration of the liberal or more practical argument with respect to the need for PP requirements within NASA. 'If I leaned in any direction, it was away from the conservative side; felt that we didn't have to take quite the precautions that other people believed necessary."

The decision favoring system-level dry heat terminal sterilization was slow in gaining acceptance primarily because we were afraid of it even when we believed it was the way to go. In that kind of procedure, everything gets soaked and nothing can be held back or protected. That is, if the sterilization temperature is 11 6OC for a given period of time, every single component in that spacecraft has got to be able to tolerate that temperature for at least that period of time. You can't keep a vulnerable component out, handle it in some special way that is less likely to damage it, and then put it in at the end. "Dry heat is so absolute, there is no walking back from it." In the end, however, there weren't many direct impacts. Some time/temperature trades were made which produced a less critical heat impact. However, heat was still a problem in the selection of many materials and parts, and particularly in the development of the tiny valves used in both the biology and the GCMS. In addition, heat-caused outgassing was a significant concern for the GCMS, and there was, in fact, one compound detected while on Mars which was apparently a residual of one of the cleaning fluids. One early victim of sterilization was a J-band experiment originally proposed for the biology investigation; it was deleted from consideration by the selection committee because the organic fluorescent-type dyes it utilized couldn't be sterilized.

The most significant lesson learned through the Viking experience is simply that a PP policy comparable to the one imposed on Viking isn't really necessary for most planets, particularly in respect to the probability of contaminating Mars. The requirement should be dropped. Even severe cleaning, in scientific terms, should not be necessary-aside from what's needed to achieve engineering or operational integrity. It should be noted that research associated with Viking sterilization identified some hardy bugs, including one they called super-spore, that could survive sterilization; this suggests that there probably were survivors on the Viking landers in spite of our sterilization procedure. Still, we now believe they could not have survived or propagated in the severe oxidizing environment on Mars, which means the sterilization procedure did little to afford PP.

In terms of technical impact, PP and contamination control requirements were simply another technical problem to solve. In terms of practical benefit, it is probable that the disciplines associated with Viking PP drove a superior hardware screening procedure that enhanced the quality of the spacecraft to some uncertain extent. That is, the severe screening process made necessary by the PP requirement (mandatory parts and materials management) identified some hardware problems that might otherwise have slipped by during the development program. This kind of discipline might, PP rationale aside, serve as a good standard for assuring the reliability of future spacecraft.

Dr. Norman Horowitz. In terms of what kind of technical impact the PP requirement or the sterilization environment had, we had little knowledge of that part of the work. "I had an awful lot to do with designing the concept of the instrument, what we wanted to do, and the laboratory work [at JPL] to verify that we could actually measure the organisms. But we weren't concerned with heat at that point, and concern about the sterilization impact didn't come into it until instrument entered actual development at TRW.' TRW never came back to us to say that something couldn't be done because of heat. While it may be possible that there were some technical problems in qualifying some of the parts or materials used in the biology instrument, "there was nothing in the PR (pyrolytic release) experiment unusually sensitive to heat." Our experiment produced its own heat, in fact; and it would be difficult to determine which heat environment was more to blame for any changes or modifications that had to be made due to a heat-compatibility requirement.

Because of the known hostility of the martian environment (lack of liquid water, very low atmospheric pressure, severe ultraviolet radiation), there was virtually no possibility that we could contaminate Mars in the first place. Earth organisms simply could not survive there. There's a new argument, as well; it's now pretty certain that pieces of Mars have been found in meteorites the antarctic. Gasses trapped in the meteorites are almost a perfect match, isotopically, with the martian atmosphere, Le., isotopes of argon, etc. And there's no reason to doubt that pieces of the Earth have probably gotten to Mars as well. 'Now, you could say, I guess, that any bacteria were probably killed in the process of tearing off a meteorite from Earth, which could be true; but I wouldn't just assume it's true without studying the question.' So there's a chance that Earth organisms made it to Mars a long time ago; in fact, that may have happened a couple of billion years ago when Mars still had liquid water on its surface, so there may have been cultures of terrestrial organisms there during that period. "It's an interesting thought!"

"I thought the surface [of the lander] should be cleaned off and sterilized, but it didn't have to be heated through and through. We were told at the time it would add 1-0 percent to the cost of Viking to heat sterilize it [the Viking lander system] thoroughly; I thought that was unnecessary." Moreover, there was never any evidence that the Soviets had tried very hard to sterilize, and they never even claimed to have heated their spacecraft. "So, if you can release bugs on Mars by crashing into the surface, the Russians certainly did it." That being the case, Mars was already contaminated before the Viking landers got there, and it was too late to worry about it. "I was concerned about the possibility of contamination in our. own cultures, but I had no concern about contaminating Mars." Thorough cleaning and clean-room assembly would have been more than adequate for preparing ail but the sample path and exobiology instruments for the mission.

Viking worked so well, however, that one has to believe that sterilization proved to be a good idea from a technical standpoint. "So I'm willing to say I was wrong"; sterilization was a goad idea. "Some of my JPL friends were saying it worked well because, since they knew it was going to be heated in an oven before it was launched, it had to be built strong to begin with; it was built to higher specifications then it would have been otherwise, and that's why it performed so well.' The real danger was our confusing the contaminants we might have carried along with us with martian bugs; that's why the lander surfaces needed to be sterilized. In any case, heat soaking the spacecraft, for sterilization purposes, produced a technically superior spacecraft. And, because heat sterilization did not turn out to be as severe a problem to solve as it was originally expected to be, it would probably be worth retaining it as a requirement for the technical benefit alone.

There was one unique contamination problem we considered during the Viking mission as a result of what we seemed to be learning from the biology results at the time. A fair amount of work had been done previously in considering and selecting hydrazine as the terminal propulsion fuel, and it was well understood in most respects. 'I think it [sterile hydrazine] was a great choice!" The more common form of hydrazine is methyl hydrazine, and they even took out the methyl so there wouldn't be any organic carbon. The purified hydrazine (N2H2) produced exhaust products of nitrogen, hydrogen, and ammonia in roughly equal volumes, which of course would contaminate the landing and where samples for analysis would be taken to a level of at least some parts per million. "Now it surprised me that there was so much ammonia, along with 0.5 percent water vapor." During studies, the exhaust was shown not to kill organisms in samples, but significant contamination of the soil by ammonia was observed. And Contamination by water vapor in the exhaust also presumably occurred, although it was not measured. At the time, the production of water vapor probably wasn't considered important; but in light of the dry, highly oxidizing nature of the martian soil, it became a much more important factor on Mars. Nitrogen and hydrogen diffused away, but the ammonia and water would have stayed and caused some changes. In the future, I'm sure the catalyst could be improved so that more of the hydrazine could be burned, and a rover would allow one to get away from the contaminated area into pristine conditions for sample acquisition or analysis.

"The lesson I learned is that it improves the spacecraft performance to put heat sterilization or something that we call sterilization on the set of requirements. The spacecraft should have to go through this heating process before we release it for travel to the martian surface. "That was a good lesson for me!" Of course, we know so much more about Mars now than we did in 1975, and that's a big lesson in itself. Everyone understands, now, how dry Mars really is and how unfriendly it is to life. Aside from perhaps some ice in one form or another, Mars is so dead geologically that it's virtually impossible for there to be liquid water (necessary to life) anywhere near the surface--although I suspect there may be some down in the core.

Dr. Gilbert Levin. When Larry Hall got the planetary quarantine committee going, it was funded, as I recall, through or with the American Institute of Biological Sciences (mid-1960's). I participated in this group for a number of years until it was dissolved. Then, concurrent with the Viking Project period (mid-l970's), 1 became particularly interested in what was then called return Mars samples. That was when the whole concept of being certain we don't unwittingly pollute Mars with Earth life or bring life back to Earth from Mars was being debated anew. So we submitted a proposal and got a contract with NASA, arid undertook a series of studies associated with planetary quarantine for return Mars samples. We must have done that for about three years.

In respect to PP and contamination control requirements for the Viking program, "I was very pleased to see that truly extraordinary steps were taken to try and prevent our carrying our. own bug with us [to Mars] and detecting it." But it did have an impact on our experiment. Initially, we planned to send glucose up to Mars. Everything on Earth likes glucose, so it was an excellent candidate nutrient. But the glucose wouldn't take the heat sterilization--it decomposed. When one considers glucose, "I would say it's a number one candidate; it's a product of classic Miller-Urey reaction chemistry, and theoretically it's identified as being a very simple energy source. Everything on Earth that we know of uses glucose--even algae, which makes glucose. If you put glucose in water, algae actually prefer it to sunlight. So glucose is an excellent nutrient candidate, and its loss to us was a very definite impact of heat sterilization.'

Nonetheless, we felt that the sterilization requirement was very good. I liked the whole concept associated with the bioshield (post-sterilization biological barrier) and how it's cap would separate in space following launch; it reflected that a lot of things had been thought through. I was told that it added something like 25 percent to the cost of the mission; I don't know whether that's so or not, but I suspect it wasn't that great and produced a number of beneficial offsets in trade.

For example, the fact that the electronic components had to withstand those temperatures probably made for better electronic components. They were really burned in by the qualification and test program and did not fail, whereas otherwise they might have. Initially, in the development of our detector, we were going to go with a Geiger-Muller counter. That's a vacuum tube device, and we had two problems that I recall. First, heat sterilization was a problem, and the other was that it probably wouldn't survive the G-shock load when the vehicle landed. The second problem was solved first when somebody developed a Geiger-Muller tube that was shock resistant well above the requirements of the mission (and the landing was softened significantly), leaving only the heat problem to solve.

About that time solid state detectors became available. And, because of those two problems and the fact that a solid state detector was very small, we elected to go with solid state detectors. We had a lot of trouble sterilizing them initially. The heat gave us false responses as though the detector was detecting radiation; and while the heat was on, we'd have a lot of spurious counts. After the thing cooled down, it would settle back down as well, but never to its original background. We worked with that problem until we had a solid state detector that could withstand heat sterilization, but I think NASA gave us some static until we were successful--afraid that we weren't going to be able to sterilize the instrument with that detector in it. Other than that, we had to be certain the nutrient would withstand the heat; we used ampules and had to be sure they wouldn't explode.

I put my trust in what was being done, physically, to deal with the PP and contamination control Requirements, rather that try to play the probabilities game. A lot of the things the Project was doing made good sense to me. I would never pretend to tell someone that our chance of contaminating Mars was only one in a million. "But when people ask me if our experiment may have detected terrestrial organisms we took along [microbial contaminants], my standard response is always that NASA's quarantine people assured us that there was less than one chance in a million of depositing a living organism on Mars.' There is no other way to answer that question, but I wouldn't personally vouch for that answer. It's interesting to note that marine life has more recently been found around volcanic vents in Earth's deep ocean trenches actually thriving in a hot environment that we would normally think of as being very nearly a sterilization environment.

We didn't have to worry about organic contamination because our detector wouldn't even respond to organic vapors if they were present. The only thing we could detect was labeled carbon (C14), and we had conceived right from the start that our labeled material was going to be contained in an sealed glass ampule. As long as the integrity of that ampule was okay, there was no chance that we could detect any false material. In thinking about the biology instrument's plumbing, however, I believe it was required that we use stainless steel. We had a little concern about stainless steel because stainless steels--to one degree or another-are or can be toxic. There was one type we found to be less toxic for our purposes, so we had to specify it as the one we wanted. On the other hand, if it hadn't been for the Sterilization requirement, we might have used some plastics that would have been better in that kind of application. The plastics, however, would have been affected by the heat, so we couldn't consider them. Another problem was that the original O-ring seals were not heat compatible. We had to acquire seals made of a special material to solve that problem.

The Viking temperature specifications (1 11C to 125%) were not too serious with respect to organics. It would decrease the shelf life of such compounds; that's essentially how one tests for the shelf life of organic materials, trading time for temperature. 'I don't think too many things would be drastically affected by the heat excursion used at those temperatures-a day or two." It's possible that there could be some reactions in addition to some degradation that would not have taken place to any appreciable degree at room temperature. About the only thing one can say for certain is that heat is much more severe for organic materials than for inorganic materials.

I felt very good about the sterilization program, so I 'never had a serious problem with what it cost us, such as in the case of the glucose. We got a very sound early start on understanding the impact of sterilization, indicating that things did get started a? an early enough point to prepare us for what was ahead. "I recall that in one of our annual reports on the Gulliver project (a biology experiment designed for the Voyager-Mars program and a precursor to the Viking program), in response to the PQ requirements, we had to provide a list of all the components and all the nutrients and analyze the impact of sterilization on them: So the Project was wise enough early enough to make us look for whatever changes we might have to make in our instruments to cope with the heat. However, I also believe there was some politics connected with it, The decisions were not always based on science and engineering, but I think that's the case in every program: it's just one of those things one has to deal with.

In spite of the fact that other modes of sterilization may still have been under consideration at that point (1967-68 period), 'I think that the only mechanism of sterilization that we ever contemplated was heat." We had reached that decision even before the Viking biology team decided that heat was also the way we were going to sterilize samples in the experiments for the controls. "There, I was not so happy, because I wasn't convinced that 160% for three hours would kill everything; especially when taking that great leap in faith and saying that if it did kill everything in a test sample on Earth, it's going to kill everything in a real sample on Mars." For that to be true, the martian organism would have to be a protein very much like ours in order to be denatured at 160%. It's easy for people now to say there's no water on Mars, so there can't be any life. But before Viking, we thought there was even less water on Mars than we think now! Mariners 6 and 7, and then 9, convinced us there was no liquid water, so we were contemplating life forms with very minimal quantities of water. If there were life forms there, they'd have to be very different from the kinds of life forms, proteins, and biochemical processes we have here; so how does one know that 160 degrees is going to kill them? And yet we went with that.

Our approach to the control issue was to use a disinfectant. We spent years developing a disinfectant that worked well for us, and we tested it against all kinds of terrestrial organisms. We did come up with a concoction that was quite effective, and we used it in our early Gulliver instruments. We had two instruments, each with an ampule of nutrient and an ampule of antimetabolite. We would shoot both instruments off and pull the string in (Gulliver's way of acquiring a surface material sample). In the one that began responding first (positive response to life), we'd release the antimetabolite onto the sample to make it a control-having deliberately selected the strongest sample because it would be the most difficult. It worked very well and I thought we had a good solution. We, of course, got the same argument I just used for heat, how do you know an antimetabolite that works against terrestrial organisms is going to work against martian organisms? We lost our case.

Viking was a marvelous Project; it was incredible how it was put together-and it worked. In the future, I would hope that we would not have to economize so much in space and weight budgets. If I'd had another quarter of a pound, I wouldn't be caught is this dilemma now. I wanted to separate the left-handed isotopes from the right-handed isotopes; if we'd been able to do that, and feed them as separate samples such that one responded and the other did not, we'd know it was biology. I proposed it, but we did not have the weight or space allocation to be able to do that. How much these kinds of things were affected by penalties due to sterilization is hard to say, but one would assume that the need to include extra hardware--like the bioshield, and heavier materials in place of heat labile materials-at least reduced some of the weight and space budget that might otherwise have been available for science.

In a future sample return mission, the sample(s) should be stored in a pristine state. What we want to do as soon as a sample is collected is test it with an instrument like an improved version of our labeled release experiment to see what it's like and if there's anything of a potentially biological nature in it. We would also like to know what the atmosphere is like and what humidity levels are present, so that we can then essentially bring back and maintain a piece of the Mars environment as well as the sample. Our Viking experiment demonstrated that something does change in a martian sample over an extended period of time, and we would want to test the sample first on Mars for later comparison. Then I'd like to. see it stored and preserved in a Mars-like environment until it can be examined here. It's feasible that by the time one gets it back, if it hasn't been maintained in its original Mars environment (temperature, pressure, atmosphere), we may not have even a recognizable trace of what was there (chemically or biologically). It's conceivable it could just decompose.

3.3.4.2 Dr. Harold P. Klein, Department of Biology, Santa Clara University, Santa Clara, CA; retired NASA/Ames Research Center and former Viking Biology Team Leader

Supplemented with technical comments by (1) Mr. Ron Gilji, TRW, Redondo Beach, CA, Assistant Project Manager for the Biology Instrument at TRW and Assistant Biology Team Leader at JPL; and by (2) Mr. Harrison Wroton, Martin Marietta Corporation, MMC Resident Manager for the VLBI at TRW.

Dr. Harold Klein was associated with the NASA Ames Research Center planetary biology studies program. While at NASA Ames, he directed the development of scientific exobiology models to determine the fEasi5ility of life that might exist in a variety of environments elsewhere in the universe. Most of the preliminary study that led to the concept for the Viking biology investigation was done at NASA Ames, and Dr. Klein was a co-investigator on the gas-exchange experiment, in association with Dr. Vance Oyama of NASNARC, before being named as Biology Team Leader for the Viking Project.

He continues to be a strong spokesman on the issue of PP and has recently authored a G-OSPAR paper with D. L. DeVincenzi (see Issues and Recommendations, Section 3.4) for Advance Space Research titled Planetary Protection Issues for Sample Return Missions, Vol. 9, No. 6, pp. (6)203 (6)206, 1989.

First, it was necessary to have a very low noise background; Le., we had to have an extremely clean, uncontaminated system. If that were not the case, our results could have been misinterpreted. Since we had instruments capable of detecting--in principal at least--a single microbial organism, given the right environment, we did not want to have a situation in which we could be confused by getting data on a terrestrial contaminant we happened to drop into the biology instrument. It was, therefore, very critical that we have the toughest safeguards possible against any terrestrial contamination we might bring along, so as to not obscure the results. That was a very important consideration.

It's difficult to distinguish between PP and the second issue, contamination control (recontamination prevention). It was really the second of these that had the biggest impact on the Viking biology investigation. Indeed, it was largely made necessary by the biology and organic investigations, because both w8re sensitive to contaminants that would otherwise have been allowed by the weaker limits of the PP policy. So exobiology imposed a tough requirement on Viking: "Namely, to be sure that whatever was done in the name of planetary quarantine for the whole spacecraft would be adequate, if you will, to assure us that the chances of a terrestrial contaminant getting in [to contaminate the biology/organic sample paths and experiments] were extremely low.

The PP constraint used to satisfy the COSPAR guideline was one chance in a thousand ($1x10^3$) for the Viking mission as a whole. When one looks at the problem of trying to determine how surface organisms and buried organisms might contaminate Mars, the first factors to emerge are a whole set of probabilities. First of all, one would want to know how many organisms make up the biological population (bioload) on the spacecraft, which can be calculated based on test sample populations and a lot of suppositions. First, you must calculate the number on the outside surfaces (surface cells-- organisms located on exposed surfaces that will be in direct and continuous contact with the sterilization heat environment); then a different set of calculations are used to determine how many organisms might be more protected within and by the physical structure of the spacecraft structure and its components (mated surface cells); and, finally, one has to calculate how many organisms might be buried within solid materials (encapsulated cells-- organisms embedded within and completely surrounded by a solid material that is impervious to the penetration of water vapor). Only after all of that is done can one calculate the probabilities that organisms might be released once transported in these states to Mars.

Of course, the probability that a surface organism could get off the spacecraft to contaminate the planet was very high, the probability that an organism contained within mated surfaces might get out onto the planet was somewhat lower, and then the probability that an encapsulated organism could get out was even lower. A surface organism could simple be knocked off. But for an organism to get out from between mated surfaces, the spacecraft would probably have to crash so that something could break open; you'd then have interior surfaces exposed, allowing any organisms previously contained there an opportunity to escape. The probability of an encapsulated organism, one that is inside a material, getting out was the lowest of all. Thai probability depended on what one would calculate for the chances either for (1) a catastrophic obliteration of the material or (2) the wind or some other erosive force ultimately abrading the component over time and releasing encapsulated organisms,

When these calculations are completed, using what was called P,, the probability that any of these organisms might actually grow on Mars, they produced a certain probability. And what we then had to do was subject the spacecraft--at least the lander and entry capsule elements of the spacecraft-- to a heat-versus-time regime. This, by calculation and mathematical analysis, reduces the number of organisms outside, inside, and encapsulated to a point where, if you multiply that final number by the Probability of Growth, you end up with the contamination probability needed to satisfy the PP policy (NASA's implementation of the COSPAR guideline).

We on the biology team were not satisfied with that degree of protection; we needed a guarantee that within the biology sample path and instrument, the Probability of Contamination should be only one chance in one million (IX~O'~)). This requirement didn't apply to the whole spacecraft, just the biology experiments, but it imposed an extra requirement that the Project had to recognize as it considered how to develop and sterilize the lander system. What this meant in practice, then, was that in addition to anything they were going to do on the spacecraft to sterilize it--clean room techniques, clean room assembly, all of that stuff--plus the ultimate [terminal VLC] sterilization (dry-heat sterilization), we then had to carry ,out additional sterilization procedures for the biology package and its sample path. Remember that we had three different kinds of nutrients on board, and they were very sensitive. While such nutrients are typically sterilized in some manner, at least one of the original nutrients choices had to be modified because of its heat sensitivity. We undertook an exhaustive test program before the mission to assure ourselves that we had this concern managed.

Basically, what was then required was that the biology instrument had to be built under clean- room conditions and procedures. It may be that the assembly of the biology instrument was conducted in a cleaner environment than the assembly of the lander itself. Then, after the instrument was assembled, if was packaged in a plastic bag that served as a biological barrier before being sterilized at TRW by itself more rigorously than the lander capsule was later. The specifications were that: "The instrument will be presterilized before installation in the lander by dry heat at 120% for 54 hours." (Viking Lander Biology Instrument, TRW Doc #21020-6003-RV-OU, August 1975.) While other packaged components were heat qualified to the same specifications, as a component-level test to insure that they could reliably tolerate terminal sterilization, the biology package and its sample-path hardware made up the only subsystem that was sealed in a biological envelope to prevent recontamination following the procedure.

How effective was it? "We might point out that the thing worked!" That is, when we got to Mars, we got no indication of terrestrial contamination in the instruments, which were extremely sensitive to terrestrial contamination. So whatever we did was adequate. And, it is worth noting for the consideration of future missions, that this incredibly complex biology instrument-with its own computer, electronics, and three miniaturized mechanical laboratories packed into a box of roughly only one cubic foot-withstood 120C (248OF) for 54 hours. "So it can be done!" Experiments with heat sterilization previously, primarily in the pre-Apollo period" (early 1960's) when people first began to be concerned about not contaminating celestial bodies, weren't very successful; e.g., attempts to sterilize a few of the Surveyor or Ranger components did not produce successful results. I think what was achieved on the Viking program is very important for that reason. Without question, the pre-Viking engineering mind-set was that sterilization looked like a virtually insurmountable obstacle.

The fact that we laid on this $1x10^{-6}$ requirement instead of accepting the COSPAR's $1x10^{3}$ requirement meant that more tests had to be done down at TRW and elsewhere (Martin Marietta and NASA/Langley) and more procedures had to be devised and implemented. There were a number of problems associated with how to ensure the instrument's sterilization prior to and then while installing it in the lander. "I know that for a while there was a problem about how to bag the instrument [for contamination protection once the instrument was sterilized], who put the instrument into the lander, and how do you handle it [to be sure it isn't recontaminated during installation prior to VLC sterilization]." At some point one had to take the bag off and put the instrument in the lander, and we were a little worried about that process. That was a potential point of vulnerability where recontamination was possible if something went wrong. But this meant only that more effort had to be put into that particular procedure, and with careful planning it turned out not to be a problem.

Ron Gilji (TRW). Technically, there was an impact due to the heat environment anticipated for the biology instrument, but it was minimal. Seals and valves had to be designed with the heat environment in mind, for example, and there were some early problems with that which were perhaps a little more influential in a less significant way-as an integral aspect of the miniaturization design problem. That is, the latter proved to be so difficult that other problems seemed superficial in comparison. "Obviously, we were always worried about the stress we were putting on everything in terms of the elastomers--those little valves. I can remember only that we had some problems with those tiny valves sticking at an early point, which I believe was a result of some special processes associated with the elastomers--they didn't behave properly when heated." It clearly was "not the kind of problem that jumped out at us" as a major issue, because those kinds of things--the selection of alternate materials or parts that were heat stable--were pretty well resolved early in the program.

There was, however, one flight instrument that did not come through instrument sterilization well, and we elected not to fly it. When we came out of the instrument sterilization with it, we seemed to have a very high background of C14 around the system in this instrument. "We never did find out what caused it or where it came down, so I made the recommendation to the-science team that they not fly that particular instrument." C14 was used in both the pyrolytic release and labeled release experiments, suggesting that its source was in one of those two experiments; but all the checks we made showed everything to be fine. We had only a very limited checkout capability following terminal sterilization at the Kennedy Space Center, but there was nothing to indicate that the terminal sterilization cycle had produced a problem for the instruments that did fly. In fact, both instruments had their best checkouts on Mars, and everything worked as it was supposed to work.

Harrison Wroton. (See Interview Summaries: Management under W. 0. Lowrie) The biology instrument was extremely complex. We sometimes referred to it as a miniature spacecraft. It had its own computer, it had a full electronic system, it had several mechanical systems, it had liquid systems, it had gas systems, it had thermal control systems, it had just about everything but its own power supply. And when you compress all of that into virtually a one-foot cube, it got to be so small that everything had to be super accurately done. We had a tremendous amount of trouble with those tiny little valves, wherein they would get contaminated and stick; not necessarily the valves' fault, but simply because it's very easy to contaminate those tiny little valves. We had many, many problems of that sort. In addition, we had our share of electronic problems that were common across the program. Thermal constraints seemed like such a problem at one point that an attempt was made to circumvent them, but we managed to get those issues back into line; the biology package was being managed essentially as an instrument system at that point, and we then pushed it to the level of a major project. Walt Lowrie called it "a spacecraft in a box,' and that's how we had to treat it.

In the final analysis, "what we ended up doing with the biology instrument was the highest level of failure analysis diagnostic corrective action activity that I've ever seen; we just had to make a religion out of doing it." It was the only salvation for us because we knew that when we got down to finishing these instruments, "we couldn't go back and diddle with them!" There was a big test series that we had to put them through prior to that point, followed by the instrument sterilization, so we had to get everything just as right as we possibly could. "And I'm really so pleased that we did, because I think they worked perfectly."

There was a point than many may remember [I 9741 when it was actually proposed that we get rid of two of the experiments and replicate the remaining experiment so that we essentially had three of the same one. The biologists opposed that because it violated their most important principle going in--that a biological investigation would NOT be conducted with only one experiment. There would be no way to cross-check the results of one kind of biology experiment with a different set of results from another kind of biology experiment, so the results from only one would be essentially untrustworthy. Fortunately, Jim [Martin] ultimately sided with us, and we kept the package intact. As it turned out, and I know the biologists feel very strongly about this, the results on Mars were so unusual that cross-analysis of results from the three different experiments has produced some extremely important insight about the martian soil chemistry. The interpretation may be controversial, but no one is arguing with the quality of the data or the performance of the experiments.

3.3.5 Gas Chromatograph Mass Spectrometer

3.3.5.1 Dr. Klause Biemann, Massachusetts Institute of Technology, GCMS/Molecular Analysis Team Leader; and Mr. G. Calvin Broome, NASA/LaRC, VPO, Manager, Lander Science Instruments Development

Supplemented by Mr. Dale R. Rushneck, Interface, Inc., Ft. Collins, GO, Viking Molecular Analysis (GCMS) Team Member.

The Gas Chromatograph Mass Spectrometer instrument used to conduct both atmospheric analyses and look for the presence of organic chemistry in surface material samples was developed independent of the Viking lander contract and was considered to be the second most important instrument on each lander. Its results were to be used to correlate with the results of the biology investigation by detecting and identifying organic compounds in the soil. Like the biology instrument, it represented a unique and highly advanced new concept for a spacecraft instrument and was nearly as difficult to develop. The following interviews summarize the problems and experience reflected in that development.

Dr. Klarrse Siernann. Only one significant development problem was experienced, that being with potting materials used to fabricate the GCMS electronic circuitry. The original potting compound could not tolerate sterilization heat or the anticipated instrument working temperature on Mars. The concern was particularly sensitive because of the mass spectrometer; if arcing occurred while the MS was exposed to the high atmospheric conductance (low pressure) of Mars, it could be badly destabilized or destroyed by corona. The electronics were isolated, and a more stabile potting material was identified and utilized; but containment of the problem was not well assured. The GCMS also experienced materials problems that affected other instruments and components as well. The more significant ones were seals and gaskets that were not heat stabile. Such items had to be made of an alternative material. One oven was lost in each GCMS carousel, but these failures are believed to have occurred as a result of errors associated with the test program and were not due to sterilization.

G. Calvin Broome. There was in fact some confusion associated with the temperature specifications for the PP requirement early in the program, and the temperature specifications at that point were quite severe as opposed to what the requirement evolved to in the end. We started off thinking that we were going to have to qualify each component or each instrument at the 145'C to 155C level, and that did not turn out to be the case. Most of the problems that resulted were in the electronic parts and materials, "and it seems to me that what we wound up doing was buying electronic parts where we could that were qualified at the part level to the extreme temperature, and then qualifying the instruments at a lower temperature that was not that much more than the temperature used for terminal VLC sterilization at the Cape.

My perception of the situation, as one who had To implement the requirement as opposed to one who understood where the requirement came from, was always that we began with a temperature that anyone would consider safe, That is, "if you cook one of these things for 48 hours at 150C, you're pretty sure there won't be any microbes left alive in there.' I think what happened along that path was that principally the electronic parts people, and to some degree the mechanisms people, probably came to the realization that they simply weren't going to be able to put reliable hardware on Mars if they had to satisfy that kind of heat-compatibility specification. So the problem was then approached statistically, with the result that the requirement was rationalized to a more reasonable level by trading temperature for time. It became an issue of probability for the continued survival of a viable organism under much lower temperatures, as opposed to the near 100 percent probability of lethality at the higher temperatures. A balance was struck that essentially met the requirements, whether they were COSPAR or NASA or whatever in origin, in terms of probabilities, and at the same time they made it possible to build reliable hardware.

A long ramp time, i.e., the time it takes to get up to sterilization temperature and then to cool down again after the period of peak temperature, is better for electronics. It's a simple matter of physics. In those days, electronics were much more transistor-like than are today's electronics parts, so they were packaged in what amounted to a can with a seal and a base, which was then bonded together as a package: the slower you ramp up to the peak temperature for these kinds of components, the less the thermal shock to the hardware. 'I think the philosophy was probably that if you had an infinitely long ramp time, you would probably achieve--baring some inherent fault in the par" result approaching zero probability of damage to the part. Whereas a short ramp time is more likely to produce damaging thermal shock that can do all sorts of nasty things that have nothing to do with the absolute temperature-just the sudden change in temperature.

The other factor has mare to do with how buried a given part is within the electronics of the spacecraft itself, and whether sufficient heat will get a chance to soak into those cold spots to achieve satisfactory sterilization-thermal inertia. The longer the time allowed to slowly approach the sterilization temperature, the higher the probability that buried parts and components will get up to that temperature before you turn the heat off and start down again. Aside from the problems we had with potted electronics, the thing one should remember about the Viking science instruments is that they were more mechanical than electronic for the most part. This implies that they were essentially open mechanisms which offered relatively little resistance to thermal inertia. Most of the development problems, therefore, were associated with the selection of materials, lubricants, bearings, and that sort of thing. And again, these kinds of problems are less severe with a gradual ramp time to and fro? peak temperature than when temperature changes are more abrupt and the chance for thermal shock is greater.

We did not treat the science instruments uniquely in terms of solving these kinds of problems because they generally affected the whole Project in pretty much the same way. But some special things were done. For example, the biology experiment nutrient media were sterilized before they were put in the ampules in which they were carried to Mars, and then the ampules themselves where sterilized. And then, of course, they were inserted into the instrument and went through the instrument sterilization regime as well. The cells in which the nutrient medium would be placed with soil sample material for the appropriate biology experiments were sterilized open rather than closed at the component level. This was done, in part, to ensure maximum heat flow within the instrument into the cell to be sure nothing got encapsulated there that would then be resistant to the outside heat. But that had to be done anyway: seats at the point where the cells closed against the bulkhead could not take the temperatures under a compressed condition--they would have deformed and failed.

Both the biology and organic investigations required contamination-free sample paths, with part of each sample path associated uniquely with its own instrument and then sharing the sample collector. The approach that was taken on the sample path itself was first to take great care during the build up, and then to develop processor and distributor assemblies unique to each instrument and deliver them to the instrument contractors (TRW and Litton) for integration with the instruments. They then went through final component sterilization or cleaning with the instrument for which they were designed after being delivered in an already highly cleaned condition. In the case of the biology instrument and its PDA, for example, the PDA was built up, cleaned, and sterilized at Martin Marietta and shipped to TRW in a sterile bag. TRW then removed it from the bag and mated it with the biology instrument in the cleanest environment possible, and then the whole combined unit was subjected to the biology instrument's final sterilization cycle. From that time forward, they were sealed and treated as a single unit, and the flight units were delivered directly to the Cape. The biggest concern in this process was that there was a potential for recontamination each time the individual elements were removed from their contamination control bags, for additional assembly procedure.

The GCMS was essentially sterilized as well, although it was really a standard Viking qualification procedure and was not considered to be a sterilization cycle in the same sense as that used for the biology instrument. It had to be chemically cleaned very thoroughly, chemically, first. Its sample path components, the PDA and its LPA, along with the CHSU, were cleaned at White Sands. The cleaning procedures for the PDA, LPA, and CHSU involved freon flushing and a heated helium purge. The cleaning chemicals and procedures otherwise applied to the GCMS were not unique, and the origin of the cleaning experience was the Apollo program. It was developed to produce the cleanest items or materials for handling and storing the lunar samples. There were a few things that had been allowable for the Apollo program that weren't allowable by Viking standards because they left organic contamination, so we made some adjustments in the cleaning compounds themselves. But there was nothing used that White Sands didn't already have experience with. We discovered very late that even the best job White Sands could do still left a residual Contamination. We considered certain treatments of the metals and implemented a few of them, to reduce some of the contamination. The best proof of our success was the absolute negative GCMS results from Mars, with the exception of traces of what was probably a cleaning contaminant which ultimately provided proof that the instruments had worked properly. The biology instrument was cleaned chemically as well, but not nearly to the extent that the GCMS was; the biology team depended on sterilization for their required protection and didn't have to be concerned about traces of organic contamination because of their controlled detector sensitivities.

The GCMS carousel produced a few problems as well, the biggest one being that the ovens were difficult to clean and relatively difficult to build up in the assembly process, And, once built, they were virtually impossible to clean at the instrument level. If a bad contaminant got into it during the latter stages that wasn't detected and cleaned out, it would thereafter produce the peaks representative of that contaminant once soil analysis got under way on Mars. Heat sterilization did enter into the problem, because it was possible for a small amount of contaminant to be vaporized during sterilization and then essentially contaminate the inside of the soil handling mechanism. Once again, however, the procedures applied to resolve these problems were thorough and very successful. Miniaturization and sterilization, taken together, probably put some limits on the kinds of materials that could be used in highly miniaturized instruments, but they did not produce any overwhelming problems from the standpoint of heat compatibility or contamination control. Miniaturization problems were more on the order of achieving the necessary tolerances in the tiny parts, like many of the valves in the biology instrument, so that they would fit or seal properly and consistently.

One of the lessons learned is that organic cleanliness for the GCMS Instrument and the path through which the Mars surface material passed was an outstanding success. As I indicated earlier, all one has to do is look at the results for certification that the instrument worked properly.

These procedures wed implemented later than some because the organic contamination control issue emerged a little later than most and was something that we implemented almost in a working environment by adapting the Apollo experience. One could extend this kind of cleaning experience out to a larger system, but it's unlikely to be accepted on its own merit for total spacecraft cleanliness in a way that would satisfy international PP policy. There would always be a dissenting voice that said you really didn't do the job.

I think the Viking PP effort was an outstanding success. The bottom line, in the case of biology, is that there was no evidence of a terrestrial biological contaminant, which certainly would have been detectable if contamination had been present. There was certainly no positive result that could be attributed to Earth organisms. Thinking back over the years and the way PP was handled, and this was not deliberate even though the result was positive, the requirements, in effect, essentially scared the hell out of the hardware people with short ramp times, high temperatures, etc. It happened this way because that was how it was interpreted at an earlier point when it was believed this was how it would have to be done. The end result was that it brought into play, particularly with respect to electronic parts, more reliable electronic parts than is likely to have been achieved with any other kind of program. When the requirements were later relaxed, the standards and procedures already in place seemed to remain intact; the relaxation didn't happen until after many of the piece-part buys were well along. The net result, therefore, was what turned out to be an extremely reliable set of components and two very successful landers. This demonstrates how important it is to have these procedures firmly and deliberately established as early as possible and to be sure that all of those involved understand the full implication of the policies, procedures, and specifications that will be in force.

Dale R. Rushneck. Dry-heat sterilization produced a number of problems for the GCMS development program. The most significant one, perhaps, occurred when the VLC-I was sterilized; the GCMS on that lander developed a leak in the vacuum envelope. There had been no previous problems with this particular instrument during any of the heat qualification tests performed on it. The leak was not serious enough to warrant a change out of the instrument, so we did not attempt to fix it because the whole VLC would have had to have been resterilized. If we had attempted to repair or change CLT that GCMS, the spacecraft my have missed its launch window.

I was able, based on the flow dynamics through the instrument when we tested it after sterilization, to pinpoint exactly where the leak was. That is, I could calculate, based on our knowledge of the instrument, where the pressure had to be in order for us to see the result we were seeing. I had it down to a fitting. `I was confident enough to say that if you take it apart and tighten that fitting, that's the one that will fix it." I then computed what the leak rate would be and determined what its effect would be on the atmospheric analysis, because that's the one we were worried about. We weren't worried about the organic experiment because the GC was connected to it, and anything coming out of the GC would have been seen independently under a dynamic condition; we would have seen peaks instead of a steady-state leak.

I computed the concentration, and then its contribution to the background in the instrument and what signals we could measure. - I was, therefore, able to determine that it would not compromise anything extremely but some of the low level measurements we hoped to be able to make. And, indeed, it did. When we tried to make low level measurements with that instrument, we weren't able to do it. Fortunately, we had the second lander on which we had a good instrument, and we made those measurements very successfully. One lesson learned; from this viewpoint at least, is that if a mission being planned has a backup spacecraft, and both land successfully, the redundancy of having a second one lessens the serious impact of having a failure of some kind in the first.

Our experience in this respect goes beyond the matter of having very nearly suffered a major failure with one at the GCMS instruments at the critical point of terminal sterilization. On VLC-2, which was subjected to wider temperature excursions on Mars because it was much closer to the north polar region, the GCMS failed just prior to or immediately after conjunction. We \traced that failure to a corona discharge in the power supply of the ion pump that kept the instrument clean. I can at least postulate a pathway back through the heat sterilization process, because the connector on the ion source housing, the connector on the ion pump housing, and all of the electronics were potted. Potting material had been a major problem at the outset of the program because the original compound was not heat stabile and an alternate was hard to find--finally provided by Hughes Aircraft. Initially, there were many problems with potting materials wherein we were trying to (1) get them to adhere to the parts and (2) to go through the thermal cycle without some of the parts pulling loose and establishing a path for corona through the module or through wherever the connection was located.

The potential for corona arcing was much greater in the GCMS than in most other components. We had high voltages running everywhere; the GCMS was driven by high voltages, And so as soon as there was any significant voltage developed, while in the martian atmosphere which has such a low pressure that it's essentially comparable to a florescent light, the GCMS electronics would have glowed like a neon light (called glow discharge) without the appropriate use of potting material, Anything that had high voltages on it was susceptible to a corona failure mechanism.

My speculation is that somewhere in the potting material used on the ion source housing connector, the ion pump housing connector, or in the electronics a path developed. Moreover, I would speculate that there is at least a significant probability that the reason that path developed was because we had to run this instrument over such a wide temperature range. If we hadn't had to sterilize the instrument, the potting most probably would have been much more reliable. The fact that the potting material had been subjected to the high temperature of sterilization may have caused a thermal expansion to where, when it experienced the early low temperatures at Utopia, the potting pulled away. If it had been potted at room temperature ardor hadn't been subjected :o the high sterilization temperatures, the potting probably would not have gone through the expansion and contraction it undoubtedly experienced. "So it's very possible, at least in my mind, that the failure occurred because we went through this real wide range thermal cycle. We don't know that, but I can postulate that mechanism."

The oven failures, one on each instrument, were a result of an error in the way test results were being interpreted. It was assumed incorrectly that a sensor light that flashed when the ovens were tested behaved somewhat erratically as a norm. It turned out that the sensor wire was open on that particular oven in each instrument. That could have happened at virtually any point, but the failure was present far in advance of shipping the instruments to Kennedy Space Center for installation and terminal sterilization and did not have any relationship to the sterilization procedure prior to launch.

Aside from those major items, our experience runs the gamut in terms of flexibility in dealing with materials. A lot of materials couldn't even be considered because they couldn't rake the application of heat and, therefore, couldn't be used. It would be interesting to explore the matter of what kinds of materials might have been used throughout the lander had we not had to find materials that were heat compatible.

If we were doing this again, electronics have improved in ways that probably would resolve some of the problems we had--although for most high voltage components, there hasn't been a lot of improvement. The thing that would have helped, in retrospect, is an increase in weight and power. If we had been given a better weight budget, for example, we could have separated components more and done a better job of isolating some of these things. We were worried about grams whereas Martin Marietta worried about pounds. There has been a lot of simplification in terms of instrument design, and that would allow better separation at the points where we experienced the potting problems.

Organic decontamination cleaning procedures used to prepare the GCMS flight articles were not new or unique, and they had been well developed on the Apollo program. The cleaning procedure proceeded on the basis of the instrument's performance, so that it essentially monitored and reported on its own cleanliness with each cycle.

3.4 ISSUES AND RECOMMENDATIONS

A failure to implement PP requirements early can be very costly to a program that will ultimately have to meet requirements comparable to those still in effect at the current time. .Moreover, most agree that certain kinds of ongoing research and development are necessary to assure that future systems will be able to meet PP requirements with minimal development and cost impact. They cite, in particular, specific materials and processes--as well as modern, highly sensitive electronic components-- as examples of areas in which an understanding of heat tolerance and effect should be pursued on a continuing basis.

The interviews conducted for this study reflect both NASA project office and contractor perspectives, identifying problems and challenges unique to each management environment as well as the solutions that proved successful in the Viking case. While future programs will undoubtedly have to address technical and oversight problems unique to their own missions and systems, it is highly probable that a review of the Viking experience will reveal many good ideas for dealing with similar problems. And, while Viking technology may be largely obsolete, this very fact--in perspective with the kinds of Technical challenges reflected in the Viking PP experience--strongly suggests the need for renewed emphasis on a continuing capability to satisfy the PP requirements.

Jim Martin. The former Viking Project Manager-feels that the Viking PP data set is 2 valuable resource, primarily due to the lack of knowledge and experience associated with this unique systems-level technical requirement. He is concerned that too much effort is being expended in the area of spacecraft technology systems with little or no concern about the potential for significant technical impact on these systems by PP requirements. He believes one of the principal lessons learned from the Viking PP experience is that such issues must be recognized and defined very early in association with any program on which such requirements are to be imposed. first, in his mind is the need for NASA and any international organization involved in this issue, e.g., COSPAR, to come to a firm agreement as to what future PP considerations are necessary, and then for NASA to place a specific and well defined policy before its projects so that there can be no doubt as to what requirements spacecraft systems will have to meet.

As far as future programs are concerned, there seems to be very little discussion of PP or contamination prevention associated with current mission studies--like those focused on Mars sample return and rovers. "I worry a little about some of the things they are talking about--robotics and what have you; if there is a tough PP or contamination control requirement, as there is likely to be, it ought to be considered up front." There are many young people at JPL and elsewhere working on these problems, and they are so enthused by the technologies they're working on that they don't realize the extent of the impact PP and contamination control requirements can have or bow that impact can enlarge as a problem the longer it is neglected. The PP requirements should be expressed in a more forthright and regulatory sense, so that people aren't allowed to forget about it until five or ten years from now when they suddenly discover that "you really can't make a widget that you can hear."

Walt Lowrie. PP requirements represent a technical challenge that needs to be understood early and at the systems level of a major program.

John Goodlette. In the future, the project and the prime contractor must do their best to first understand the major factors that establish the standards and must then be sure that subcontractors understand the requirements as well as possible and as soon as possible. Moreover, anytime there is a major development subcontract like the one used in association with the biology instrument or the computer, the prime contractor should plan on having a technical team in residence from the very beginning.

Joseph Stern. We need to be looking three to five years downstream on, a continuing basis to be sure that state-of-the-art parts, materials, and components will be available that can survive sterilization or meet PP requirements. I would recommend a long-lead research and development program on materials and processes.

As suggested in the first section of this document, it is likely that new PP policies and technical solutions will be necessary to deal with the challenge of returning samples to Earth, which produces new requirements associated with protecting sample integrity and assuring against back-contamination; very little of the Viking experience addresses these issues technically or philosophically.

This being true, everyone agrees that much needs to be done at a very early stage with respect to PP policy and technology and that not nearly enough is being done at the present to prepare for that eventuality.

3.4.1 Dr. Richard S. Young, Cape Canaveral, FL; Former Viking Program Scientist, Exobiology Manager and Planetary Quarantine Officer, NASA Headquarters

Dr. Young was chairman of the life science experiment selection process for Viking, which led to his Viking Program Scientist role. He also managed the Exobiology Program at Headquarters at the same time, which included life science and organic chemistry research projects that became the basis of the Viking life detection [VLBI] and molecular analysis [GCMS] investigations. He later served as Planetary Quarantine Officer at NASA Headquarters, following Larry Hall's retirement and preceding Donald DeVincenzi in that responsibility.

3.4.1.1 Viking Biology Experiment Selection Process: Sterilization Heat As a Selection Factor

I recall only one experiment that was rejected because it could not be sterilized. It was called the J-band experiment. It involved the use of an enzyme, and enzymes are not heat stabile. It was rejected for that reason, although the experiment itself was not well suited to our requirements and probably would not have been selected in any case. It is perhaps important to note, however, that the implication of this was that heat sterilization 'did rule out a certain category of experiments-any experiment that included an enzyme." We ultimately selected the only four that had any real meaning according to what we knew about Mars at the time; you can always, in retrospect, design better experiments, but I was reasonably well satisfied with what we ended up with at the time.

Wolf Vishniac's experiment was later dropped to help overcome some of the problems with cost, volume, and schedule burdens being experienced with the development of the VLBI. "Wet" is certainly a key word, but the Vishniac experiment was probably the most geocentric (Earth-like in its expectations for Mars) of the selected experiments. It had to assume that life on Mars was pretty much like life on Earth in order to work. In contrast, Norman Horowitz's pyrolytic release experiment was the most Mars- like of the experiments.

In terms of why it became necessary to drop an experiment, however, it probably wasn't simply due to economic pressure and the desire to eliminate an experiment that seemed too Earth-like. 1 always thought there was another parameter which bothered the Project manager. I think, at least at the time, he would have argued that there wasn't enough space for all four. The instrument was simply too complicated and required too much engineering, and it was becoming evident that more room was needed by the experiments than could be afforded in the small space allocated for the VLBI package. The effort to miniaturize the VLBI was by far the most significant factor, pushing the cost of the biology science instrument many times higher than had been anticipated. Complexity was always a major issue--everyone greatly underestimated the complexity of it. There were more tiny valves and lines, more of this, and more of that, than anyone had anticipated, and trying to compress all four experiments into one cubic foot or so of space was asking too much.

3.4.1.2 Sterilization Considerations

I would agree that a major serendipitous side benefit of the heat qualification process was a uniformly and highly reliable spacecraft, 'and it's good to know that there is now a consensus of agreement with this fact--even among those who were not advocates of the need for sterilization of the entire spacecraft. In reality, the heat sterilization we used on Viking amounted to a relatively benign process once the proper materials had been selected. The temperatures involved weren't so very high, and modern electronic components and materials typically survive at heat levels approaching sterilization temperatures. While the sterilization requirement may very well have guided the selection process for some of the materials used, however, those materials were available and did not force a major new-technology issue for the VLBI instrument package; we never saw heat sterilization as a problem for the biology experiments.

We were certainly aware at the very outset that if we were going to follow the rules, we were going to have to sterilize at least the life detection experiments. So there was never any question in our minds that they had to be heat stabile. in terms of life science, the experimenters had to be aware of that requirement. They all agreed that it would not be a problem. Sterilization wasn't particularly crucial for them; all nutrient solutions used in laboratories are sterilized, usually with steam under pressure in an autoclave, The only impact I remember was a nutrient Gil Levin had hoped to use which was not heat stabile, but he was able to modify his medium without great difficulty. Gil was otherwise a strong advocate of the PP sterilization requirement.

However, we were concerned about sterilization from the perspective of Viking program science other than biology, because it may well have produced problems for some of the other experiments that had never encountered sterilization before. We had to get the investigators thinking about it early, in terms of heat stability associated with some of their parts and materials. The Gas Chromatograph Mass Spectrometer (GCMS-organic chemistry molecular analysis instrument) also came out of my program, in that organic chemistry is an element of exobiology. Klaus Biemann, the Viking GCMS team leader, was a grantee of mine before, during, and after Viking.

In the GCMS, the most significant concern by far was really one of potential organic contamination within the instrument, compounded again by the fact that the primary cornponents4he mass spectrometer, the gas chromatograph, and the carousel that contained the sample pyrolysis ovens--were extremely miniaturized and compressed compared to their conventional lab counterparts at the time. The interior of the instrument had to be chemically cleaned, which is not unusual in itself but was made difficult because of the miniature nature of the components and the fact that its high voltage electronics would have to be heated. Unlike the biology instrument components and mediums, which are typically sterilized in any laboratory environment and therefore posed no new challenge, the GCMS is not an instrument you would normally sterilize.

In the beginning, there was some concern that the GCMS could not be cleaned adequately, but I believe that soon proved to be a workable problem. We were much more concerned that the samples the GCMS acquired might be contaminated from/by the spacecraft--from fuel combustion products, for example. This had been a concern during two different periods--first, as we considered the terminal propulsion issue during development and, later, during mission operations when we realized that some of the surface samples were being taken from potentially exhaust-contaminated areas. Indeed, there were many concerns about what the landing itself was going to do to the surface material, and they were all very valid concerns. There are organisms that can live in solid rocket propellants, and even some that can metabolize rocket propellants, including hydrazine. Hydrazine was selected for the Viking lander's terminal landing propellant partly because of its natural toxicity, but it still had to be purified: even then it's conceivable that some organisms were still alive in it, although it's very unlikely they survived the terminal propulsion bum. The point one needs to remember, perhaps, is that if you've got an organic compound to worry about, it's highly probable that somewhere there is an organism that can break it down sooner or later.

3.4.1.3 Recommendations for Change

There will always be a question as to how successful sterilization will be; e.g., is it as effective with lower temperatures and longer heat soaks? As a result, sterilization will probably remain a highly statistical kind of thing in terms of how we consider it. We know, statistically speaking, what factors contribute to the ability to sterilize and how these factors can be adjusted to fit the system margins afforded without compromising the statistical probability of achieving sterilization. If the temperature specification is lowered somewhat, and the soak-time is extended to compensate, as in the case of Viking, the same statistical degree of sterilization can be achieved. But it still comes down to the fact that if you’re going to say that the spacecraft is sterile, you're saying it's sterile based on statistical evidence. And it may or may not be, even though everything we know strongly suggests that it is.

I believe we need to take a slightly different approach, philosophically, to mission planning. We need to be able to say: look, our goal in going back to Mars and returning a sample or doing in situ experiments is science-science is the objective. Once these large goals are established, we can establish the requirements needed to help us to achieve them. If we're going to return a sample, for example, we must take great care not to contaminate the sample or destroy its potential products. That means we have to acquire it without contaminating it; we have to seal it up, return it to Earth, get it into the laboratory and behind a barrier without contaminating it. Note that I haven't said anything about quarantine; I said we've got to avoid contaminating the sample. And that's crucial. There's no scientist alive who would argue with that, and the public wouldn’t argue with it either. By taking this attitude, we are effectively quarantining the sample and preventing contamination in either direction. So it's just a change in the nature of the argument and in the way it is posed, and I think that might overcome a lot of the controversy. Just lay it on the doorstep of science; hey, we've got to protect the sample, that's what it's all about and that's what we're going there for in the first place! If we do a thorough job of that, everything else will fall into place and take care of itself.

I am in agreement with Chuck Klein's feelings about PP policy, in that it's probable that many of the same concerns we had prior to and during the -Viking program, particularly with respect to PP as it relates to the biology issue, have not been resolved in a way that assures us they will not become issues all over again in the future. Indeed, there is a reasonably good probability that they will be debated in a public way and with the public playing a key role. It's not that we didn't learn anything from Viking, but we created as many new problems as we solved. So Viking did open a Pandora's box, and it is probably going to come back and haunt us. The whole specter of organisms on Mars and the potential for back contamination is going to come up again. That's why we're starting up right now with a working group on PP. We've got to go back over all that ground again and see where we are--what we should anticipate.

3.4.2 Dr. Donald L. DeVincenri, Space Science Division, NASA/Ames Research Center, Moffett Field, CA 94035; Former Planetary Protection Officer, NASA Headquarters

Dr. DeVincenzi succeeded Dick Young at NASA Headquarters in 1979, taking on the task of Planetary Protection Officer. And, because that was the post-Viking period, much of the interest in PP at NASA was ebbing between 1979 and the present. The most significant activity during the period was that of developing a more relaxed PP policy on the basis of a series of studies. The policy was reviewed and adopted by COSPAR in 1984; since that time, NASA's PP policy has been the same as COSPAR's. It represents a liberalization of the requirements that were in effect at the time of Viking.

With respect to COSPAR and its original guidelines, which are so difficult to get a handle on, the guiding principle is the space treaty that served as the ultimate product of the original agreement, Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space Including the Moon and Other Celestial Bodies (1 967). It laid out the concern for protecting the planets during a 50-year period of exploration between 1968 and 2018. The United Nations looked to COSPAR to essentially administer the policy. There is always some confusion as to whether COSPAR is regulatory, but I have never found that there is any regulation. It's simply a political treaty that all the parties agreed to honor under the auspices of the United Nations. COSPAR doesn't have any administrative teeth or any policing authority but did try to develop the provisions of that treaty into an international set of procedures that roughly complied with their interpretation.

Since that time, NASA, COSPAR, and other member states have redefined, reiterated, and revised the policy through its various incarnations. In about 1980, NASA decided that there were good reasons to revise the policy, and it had the net effect of reducing requirements. NASA took that revised policy to COSPAR and said we think it's a good idea for you, COSPAR, to examine and adopt this policy. GOSPAR essentially agreed, and the NASA policy is now the COSPAR policy., Another revision is being worked on at this time that is intended to overcome the arbitrary nature of the existing policy, which essentially states that there is a quantitative limit that could not be exceeded for all the planets and all kinds of missions.

The revision makes that statement more qualitative, so that it now depends on the nature of the mission--whether it's a lander or an orbiter, orbiting or on the surface of the planet, and distinguishes between planets like Mercury and Mars. In that sense, then, the new policy is much more realistic. It implies the greatest amount of concern for landed missions to Mars as opposed to less concern for orbiters to Mercury, for example. Under the old policy, the same planetary requirements would have more or less been imposed on both of these missions. The revision will also take into account knowledge of planetary systems up to the time of the policy, which means it takes into account all of the Viking information about Mars and a lot of the information about the outer planets acquired more recently by the two Voyager spacecraft. That also makes the application of the policy much more realistic in terms of the missions being planned.

With respect to the 50-year span of the original COSPAR agreement, how long the period of the policy application should be or whether it should be extended are not major issues. It's clear that we were overly optimistic. There's no real argument to extend the period, and I can see in a sense an argument to shorten it. Our exploration of Mars is not going to be as intensive as once hoped, and some of the biological emphasis is going away. A few more good missions, beginning with an orbiter like Mars Observer, followed by a set of fifteen or so penetrators a few years later with some good chemical experiments and then a rover and a sample return, and we will have characterized Mars' biological potential very well. I believe we will know enough about Mars at that point to know whether PP is still a real issue. In other words, the issue of PP will be resolved before we send manned missions to Mars.

It makes sense that it be resolved before we send humans, because once we've done that it's too late. Contamination will be unavoidable, In this way, the period of PP becomes dependent on how long it takes to perform these precursory missions. If they happen to take another twenty years, then it will take us twenty years to get the answer. But if they happen to be done between now and the year 2005, then that's how long PP needs to be in effect. The question is how long will it take to get the data that will convince us that we have the answers we want.

At COSPAR in Helsinki a year and a half ago, we had a session on planetary quarantine with regard to a Mars sample return mission. Everyone was sensitized to the fact that there are mission planning studies going on right now that we're not paying much attention to. There is a need to bring PP issues to the attention of mission planners at the earliest possible time. Because our experience with Viking was that PP and contamination control costs a lot of money and needs to be started early, there might be other ways around it. So during that session at COSPAR, we laid out a set of general guidelines that could be used by mission planners. It's not policy because it has not been signed by NASA, but we did lay out a set of general procedures for a sample return mission that involved things like partial sterilization, sealing in a bioshield, hermetically sealing a sample on the surface, breaking the contact between the surface and the sample-return mode, and bringing the sample back to Earth behind some sort of a barrier system.

We felt that these guidelines were enough to get mission' planners started, pending the development of more specific details. For example, I don't know anything about breaking the contact chain between the Mars surface and the sample container on the way back, but I assume there are technical people out there who do know a little bit about that and who should start studying it--it may be one of the toughest problems. Maybe we don't need to know more than-for now, at least--just that we need to break the contact chain. If so, that's the only specification we need to provide in that case. We simply ask our contractors, how do we break the contact chain, and how much will it cost?

I believe John Rummel [current Planetary Protection Office, NASA Headquarters] has taken those guidelines and essentially asked the mission planners to use them as an example of the kinds of things that might be levied on a sample return mission. So we have at least established these preliminary, very qualitative proposed guidelines for the mission planners to use if they have the information. Are they well enough defined to have specs written on them? I don't think so. But the mission isn't defined well enough to have specs written for it either. These things must progress in parallel. I think we've started at a level commensurate with the level of activity going on with the mission itself; once the mission becomes real, we'll then see PP become real. Coming up with these guidelines gave us some clues as to where additional work might be needed and which could be supported right now--like what it will take to break the surface contact chain. I don't know how it might be done, but I can imagine that we need to spend some money to begin studying concepts and ideas on this issue.

We know a lot already. We know how to do partial sterilization. Heat sterilization worked well with Viking for spacecraft systems, so why not do it again, The bioshield--we know what we're doing there. But I don't know that we know how to break the contact chain, and I don't know that we know how to do hermetic seals. Preserving the sample at ambient pressure on the way back probably isn't a technology barrier, and analyzing it back on Earth behind a barrier is not a technology barrier. So out of these five or six procedures, only two of them probably require any preliminary hard study.

We're sitting in reasonably good shape at this point, but we can't wait too much longer. At some point PP issues begin to become critical in their absence. . People are actually spending money right now on designing things like the sample acquisition system; for example, drills and other ways to collect samples. If they're developing the' prototype hardware, then we should be doing related kinds of things for PP. And at the point where they're starting to develop subsystems--sampling devices, containment devices, proof-of-concept models--we should be doing the same thing with some of the key PP issues. The direction and the money has to come from NASA Headquarters. The PP officer has to tell whoever is managing the sample return studies, you must start looking at these impacts. They, in turn, have to tell their people at JPL and JSC, who in turn have to tell their contractors, and so on and so forth. That's the only way it's going to get done.

The fear of back contamination is going to be a major issue. People can talk about how there won't be any major requirements all they want! but there will be just the same. We've got to start thinking about it now and face the issue while we can still do things properly and in good sequence" and when it won't bring the project to its knees. These procedures that we propose for study are not, I don't believe, very stringent. Except for one. And that one happens to be the key one for back contamination--breaking the contact chain with the surface.

Even though the serendipitous benefit of the PP requirements and procedures imposed on Viking may very well have produced a more reliable spacecraft, and it is perceived as a benefit in that sense, one must produce proper reasons for imposing PP controls. I think that the new policy we've proposed will at least give everyone working on the mission the best possible way to tailor the planetary quarantine requirements to that specific mission and do it in a way that will have minimal impact on the mission. At least the potential is there in the policy as written.

3.4.3 Dr. Harold Klein, Santa Clara University

The question of whether PP should be an issue was argued very strongly between the pro and con camps prior to the imposition of the Viking program requirements, and it will be argued again. It all comes down to a question of almost religious faith as to whether the pail is half empty or half full. Josh Lederberg and Carl Sagan were convinced that there was a good probability that we might find some kind of life on Mars in those days. Even Norman Horowitz was originally a proponent of going to look for life on Mars, and he began to develop the concept that ultimately became his pyrolytic release experiment way back in the early 1950's.

It wasn't until the Mariner data and some Earth-based astronomical data in the late 1960's that we began to get a sense of how dry Mars really was. Originally, we were thinking that the atmospheric pressure was up around 20, 25, maybe even 35 millibars; then someone discovered that it was much dryer there and that the atmosphere was very thin. At that point, Norm began to think much more seriously about the negative environmental characteristics that are now the core of his argument that life as we know it can't exist on Mars. That debate extended into the time just before Viking when people were considering the importance of sterilization. That's when Norm began saying, you don't have to sterilize anything because terrestrial organisms can't possibly grow on Mars--the environment there is simply too harsh.

However, others felt that: (A) there might be a better chance that there are more martian organisms than Horowitz believed and (B) that the environment really wasn't that detrimental to terrestrial organisms. These same arguments continue to be debated even today. The people who know Mars better are probably more likely to say that it's too harsh an environment for life. But those who are newcomers into the field are more likely to argue that life may still be possible there. So I'm sure we're going to hear the same arguments all over again.

Recent COSPAR meetings have afforded special sessions on PPI either workshops or symposiums. There is a cadre of people--some from the United States and some from the European scientific community, but none unfortunately from the Soviet Union--in this corps. It gets together at COSPAR and discusses problems related to planetary quarantine. It is my opinion that the European scientific community is, if anything, more concerned with PP issues than is the American scientific community. And the reason is very complicated. The new ingredient that is now being mixed into the PP picture is the global environmental movement, which reflects the concerns of the public through special interest environmental groups. This being the case, what we may ultimately have to face isn't even a scientific question-but one of public confrontation and interaction.

This environmental awakening is now another force we'll have to contend with, and it seems to me that it will become the major driver. There are those who will motivate the public, arouse the public, and even scare the public about the very issues the PP program was designed to resolve in the first place. And the real concern that NASA ought to be addressing for the future is how do we devise a PP program that, on the one hand will make good scientific sense, and on the other will be the least expensive program that will satisfy the majority of the environmental concerns the public almost certainly will raise. The public fuss raised with respect to the Galileo RTG's is a good case in point; it actually got into court and to a stage where an injunction was being sought only days ahead of the launch window, all because of environmental concerns over the grossly improbable chance that radioactive materials might be released catastrophically. In that case, however, the program had done a lot of work over the past few years in preparation, and that's the kind of effort it's going to take to deal with these issues in the future.

I feel that NASA needs to be doing something similar to that right now, in respect to preparing to deal with future PP questions. Planning step by step, NASA ought to begin to pulse the public sentiment on these issues, This doesn't necessarily imply that poles need to be taken, but we ought to be talking to people who typically deal with the public about these issues. I've already explored this subject with some newspaper science writers to determine how they might feel about the PP issue in regard to Mars sample return, and it's clear that they feel there could be a real problem raised by environmentalists, Moreover, science fiction gets very confused with reality for a lot of people, and we will be dealing with images of The Andromeda Strain and a lot of stuff about creatures from Mars. These images, coupled with legitimate environmental concerns, could become a serious problem for us in the very near future.

Norm Horowitz, taking his argument as a prototype, will probably be unsuccessful in convincing most of the younger scientists that we don't need a PP program. No matter how bleak a picture he paints of Mars, no matter what arguments he uses, that we can't contaminate it and it can't contaminate us, he will not be able to convince the biologists who haven't really ;looked at Mars that we shouldn't continue to look for life there. Some of them will say "gee, terrestrial life is very adaptable," and that opinion will have a high enough stature to win support. After all, organisms can grow in 2OO0F water on Earth's ocean floors, so how do we know that they can't find some little niche on Mars? None of us can resolutely say that isn't possible. it's comparable to the statistical game of probabilities we play with the lethality of sterilization regimes for microbial populations. And if we can't say that there's no chance for life on Mars, the alternative is to take a fail-safe position and say, well, then, we have to sterilize.

The same is true for those very practical arguments about how little chance there is for back contamination. That is, if there is a biota on Mars, it's DNA--whatever it uses for its nuclear information system--can't possibly be the same as is found on Earth and so, therefore, it cannot infect us. But then someone says, well, how sure are you of that? Oh, very sure. Give me a number. One chance in a million. Yeah? One chance in a million? Sounds good but, well, I don't know. Let me see, there's five billion people on Earth, and there's IOi5 billion organisms--plants, animals, so forth--not very good odds! So, statistically, it's a no-win situation, and we'll have to sterilize.

NASA will then have to consider what constitutes a reasonable sterilization protocol. In addition, there is the whole spectrum of things to consider in respect to the back contamination issue. We came up with a huge protocol while I was on the Lunar Apollo back contamination committee, for example, and I don't think we can do it that way with a Mars sample. Scientists will almost certainly want to have some kina of intermediate stage where some testing can be conducted. But I don't believe we can go along in our closed sessions planning all of these things, writing out protocols for programs and for PP, and have years go by before--say, in 1997--we suddenly announce that we have a PP plan for Mars sample return. At that point it may be too late to stem a tide of negative public opinion that might suddenly arise. We should somehow be bringing the public into the issue now. We don't have to make a big deal out of it, but we should be planning some kind of interaction and sounding the public in certain ways, perhaps through academia--maybe by publishing certain kinds of things in the public media and studying the feedback we get, maybe even by talking to some of the more responsible environmentalists and drawing them into the planning.

There is a broad spectrum of environmental interests in the United States. A few of these interests are magnets for groups which have such extreme views that we'll probably never be able to satisfy them. But the majority are represented through a large middle zone of responsible, rational environmentalists who, if we brought them in now and discussed our plans and procedures with them, could be very constructive through their participation. And, by defining our plans for protecting Mars and Earth, which I'm sure they would be concerned with, we would be the beneficiary of their feedback while earning both their respect and their support as we moved forward. That would be the position I would try to advocate, one of mutual respect.

I should mention one new ingredient in this whole PP matter that I find to be quite interesting. Beginning primarily during the mid-1960's, just prior to and then during the Viking program, there was an almost universal denigration by the physical science community of the biological interest in Mars. Important, highly influential physical scientists had come to the conclusion that Mars was a dead planet. They publicly sneered at any serious interest in Mars that did not reflect their own, and they made it clear that they thought it was fruitless to invest important resources in looking at the problems associated with the possibility of life on that planet; they felt it would be more useful to put that money into geology, atmospheric physics, or in virtually any other science but exobiology. I would be the first to recognize that there were some very reasonable and worthwhile science interests defined by their arguments, but the principal point of those arguments was that the biology issue wasn't worth thinking about or undertaking. Indeed, there were many instances along the Viking development path in which the physical science community tried to either shoot us down or cut us down to a much smaller size.

What I find very curious, currently, is that there is more optimism in the physical science community on the biological questions about Mars than there is in the biology community itself. This is certainly a very interesting sociological reversal. When I go to meetings, Mars workshops, etc., I find that there's almost a surprising optimism among the geologists, seismologists, and other physical scientists for going back to look for life on Mars again. NOW they want it! Fifteen, twenty years ago, they were totally against it. The only reasonable explanation, to my mind, is that they've come to realize how powerful and important--through public appeal--the life issue is as a justification for new programs. They saw how well it worked in the case of Viking, and they realize that money is very tight today. The optimism being expressed worries me, because some of it is excessive to the point of being a sham.

These pseudo exobiologists have found new ways of focusing on biology that do not seem to be biological to the untrained, such as the search for fossil evidence of past life. I consider that to be a biological issue. That concept arose after Viking because it wasn't until later that we began to contemplate the age of fossils on Earth and to wonder if Mars might then have a fossil record from a time when its liquid water and atmosphere may have supported 2t least a minimal biosphere. The same people who were ready to walk all over us a few years ago now act as though they are praying for us. Why? It can only be because they feel that without us the missions are not going to be approved. I find that to be dangerous because they can easily overstate the case. The issue of water on Mars is a good case in point. While the geologist might think of the kind of ice that is distributed deep in the regolith as water, to a biologist it's not; the kind of water they are talking about wouldn't support a viable life form, but the use of the word water suggests a possibility for life to the average person that isn't very realistic in the context of the otherwise hostile martian surface environment.

It seems ironic that NASA is adopting this kind of position on the life issue for Mars and yet is so weak in its recognition of the importance of PP when it is so crucial to any scientific effort to find that life. That's a very ambiguous position. In October I went to a meeting of the NASA Advisory Council (a high-level, policy-recommending group of people associated with the Office of Exploration, the Smithsonian, and the Library of Congress) in Aspen, Colorado. I made a point about this PP issue, spending a lot of time trying to impress them with the fact that, yes, these missions are great, but that we've got to work in this whole question of PP--recognizing also that imbedded in it is the public affairs issue associated with the environmentalist movement. I tried to make them understand that we weren't going to be able to sweep it under the rug. I think they were impressed by that.

The original intent of- the early discussions on the quarantine of Mars was to preserve that planet during the period of biological interest. There was to be a period of time during which all the nations of the world would be sending spacecraft to Mars. They agreed that during that period they would not contaminate the planet for anybody else. But to get a fix on how long that period would be is slippery. The original wording left it open, but then it was interpreted for the treaty to have a 50-year term (not by COSPAR); that period began in 1968 and ends in 2018. Others have put a 25-year limitation on it.

Generally, the period is based on how many missions would likely be needed during the period of biological interest to settle the biology issue. All of the estimates on how many missions it would involve were very high, and it's pretty clear now that both the number of missions proposed and the time allotted them by agreement were excessive. Does the quarantine period end at some date even if there are no missions? Does it end after a period during which 200 missions are flown, or 100 missions, or 50 missions, regardless of the date? The intent certainly wasn't just to put an end date on the period, it was to reflect an estimate for a certain presumed number of missions to conduct the biological investigation of Mars.

If you asked COSPAR representatives today about how long the agreement would be in effect, and if you asked them what we should do about it, they might say, well, if there was a defined period of.50 years, twenty-five have gone by and we doubt that in the next twenty-five years we'll do enough to resolve the purpose of the quarantine; therefore, let's push the date out as much as we need to in order to get the job done. What's intended is to assure a period during which you can adequately assay the planet to look for life and its precursors. I can't give you a date. NASA could take the position that there is a 50-year limitation, but I don't think that would satisfy the public. I feel that the top management of NASA ought to at least listen to some of these arguments, and then they ought to devise some sort of a policy. That policy might be that we no longer concur with the COSPAR agreement and that we're not going to honor it any longer. Or it could be that we're going to do whatever we can in the next few years to revise the COSPAR basic guidelines. Or, finally, NASA could say, we will live within the COSPAR guidelines and won't disregard them or change them: then we should at least work at defining what they are so that we know exactly what it is we're going to live by.

We are in a tough situation. If we continue to drift, we will then expose ourselves to the kinds of public criticism that I'm sure are going to come in any case. But if we're dealing with a wishy-washy set of guidelines and we try to implement them, we aren't going to accomplish very much of anything and we're going to get into trouble. One of the reasons we're not getting better cooperation from the spacecraft people is because they need specific requirements, and we aren't providing those specific requirements. The easiest thing for them to do is nothing. I think it would be important for NASA's top management to be exposed to some of these questions, and to then either immediately or after some study, come up with its own internal policy. Not just a policy that meets the COSPAR guidelines, which is what we have now, but one that everyone clearly understands. Because there are no clear guidelines: the Soviets can do one thing, and we can do something else, because we're all interpreting a very loose, poor set of guidelines. I don't know what to suggest; all I can recommend is that this question not be left dangling. It keeps pushing off potentially expensive decisions, because the longer we wait to be responsible with PP, the more expensive it will be to execute when we finally have no choice but to face it.

3.5 TASK SUMMARY

Lessons learned from the Viking experience impresses one with the uniqueness of the Viking program--what it did, how it did it, what it represents-as a technological/managerial experience resource for future programs, and how truly unique and important the Viking experience is in its significance as a model for what lies ahead. No other program is its equal, for no other program, evolved as it did or accommodated such a broad range of requirements associated with such extreme environmental considerations. The Viking Lander Capsules were the first planetary spacecraft systems designed and developed from the start not only to be fully sterilized but to carry insurance of that sterilization into space. To achieve this, they not only incorporated unique system components to help assure the integrity of the sterilization procedure but also frontally assaulted the whole issue of heat sterilization at a time when state-of-the-art technology and heat were still incompatible. Viking was more than a spacecraft that went to Mars and landed; Viking was the trail-blazer and the pathfinder for NASA's important future missions. One cannot emphasize the significance of this experience enough, and to ignore it in any way would be an act of neglect.

The lesson learned for PP experience (in Viking terms) is that the Viking experience may well reflect what PP should be like rather than how it is presently perceived. That is, rather than being generally defined, PP should be well defined as a requirement with sufficient structure and authority to command early definition of the specific requirements, acceptable detailed methods/approaches to satisfy the requirements, as well as early implementations into future program studies to assess any technology development necessary for the program hardware to meet the requirements. Don DeVincenri suggests that 'it needs to be high on a flagpole where everyone can see it"; and Jim Martin admonishes, "it needs to be out in front as both a standard and a filter for systems-level implementation.' Viking is not only a remarkably successful example for this kind of PP policy and implementation, but it is the only example we have. One could not imagine a better model for the future.

4.0 TASK 3 (2.3 of SOW)

This task requires a review of current NASA and COSPAR PQ requirements and an evaluation of the influence of any changes from the Viking era criteria on the overall PQ environment applicable to future Mars missions.

4.1 INTRODUCTION

At the present time, NHB 8020.12A and NMI 8020.7A are the only two active and significant NASA documents related to planetary protection policy and constraints. These documents establish a wide range of requirements through their implementation in order to allow flexibility in satisfying planetary protection concerns. Theoretically, this may allow a project considerable flexibility to satisfy these policies. However, if the detailed engineering requirements are not defined and implemented in a timely manner, the delay could have significant impacts on the project and recovery could be extremely difficult and costly for the planned program. Figure 4.1 provides the history of the NASA planetary protection policy/requirements documentation.

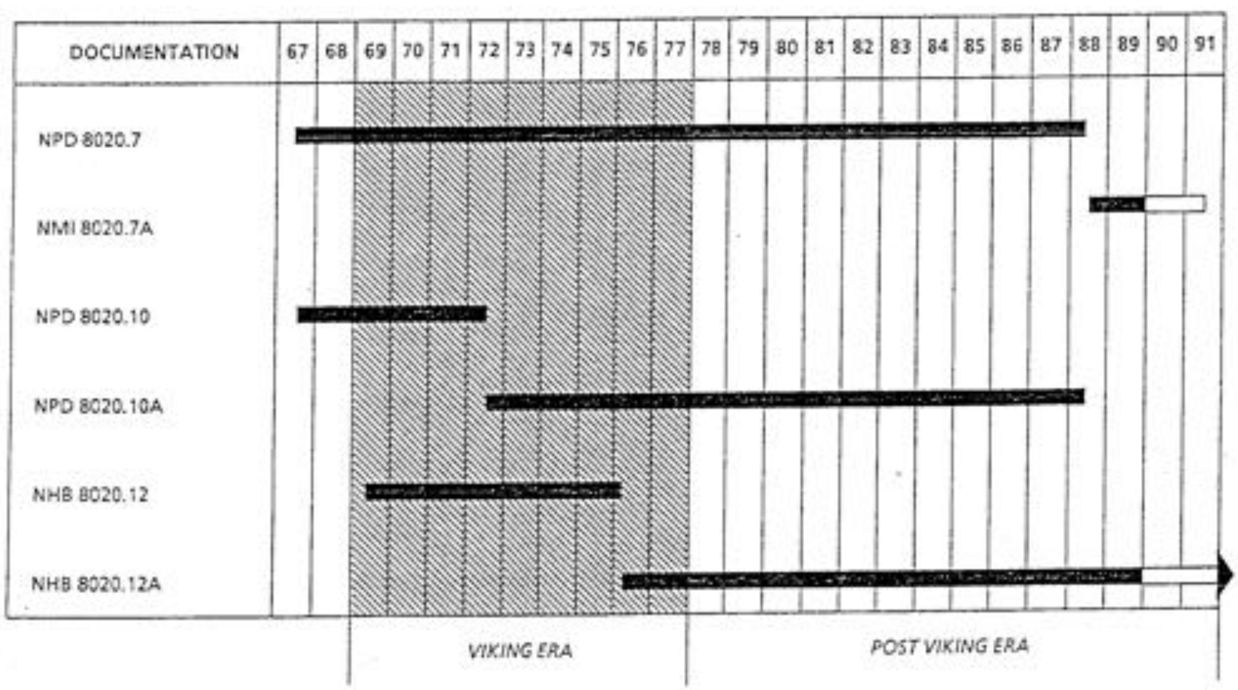

Figure 4.1 - NASA Planetary Protection Policy/Requirements History

The requirements that planetary protection imposed on the Viking program at its inception were contained in three documents. Two of these were NASA Policy Directives (NPD's):

(1) NPD 8020.7 -- Outbound Spacecraft: Basic Policy Relating to Lunar and Planetary Contamination Control, dated September 6, 1967.

(2) NPD 8020.10 -- Outbound Planetary Biological and Organic Contamination Control: Policy and Responsibility, dated September 6, 1967. In 1972, NPD 8020.1 OA was released effective August 1, 1972, to cancel and replace NPD 8020.10. This revision document incorporated specific organic material-identification-and-storage requirements to be imposed on flight projects. The policy authority of NPD 8020.1OA ended May 4, 1988, as noted below.

(3) The third document was a NASA Handbook (NHB), NHB (3020.12, Planetary Quarantine Provisions for Unmanned Planetary Missions, dated April, 1969.

4.2 POST-VIKING DOCUMENTATION

Since the Viking era, NASA Management Instruction (NMI) 8020.7A, Biological Contamination Control for Outbound and Inbound Planetay Spacecraft, was released effective May 4, 1988, with an expiration date of May 4, 1991. This document cancelled and replaced both NPD 8020.7 and NPD 8020.1OA. NMI 8020.7A added the back contamination policy, intended to protect Earth from potential hazards posed by extraterrestrial matter on spacecraft returning from other planets, to previously established policies protecting other bodies. It also assigned specific responsibilities to three areas: (1) The Associate Administrator for Space Science and Applications; (2) The Associate Administrators for Space Flight, Space Station, and Space Operations; and (3) Program Directors. And, more notably, it incorporated "Mission Constraints' that imply a reduction in previous requirements and reads as follows:

MISSION CONSTRAINTS

Specific constraints imposed on spacecraft involved in solar system exploration will depend on the nature of the mission and the identity of the target body or bodies. These constraints will take into account current scientific knowledge about the target bodies through recommendation from both internal and external advisory groups, but most notably from the Space Science Board of the National Academy of Sciences. The most likely constraints on missions of concern will be a requirement to reduce the biological contamination of the spacecraft, coupled with constraints on spacecraft operating procedures, an inventory of organic constituents of the spacecraft and organic samples, and restrictions on the handling and methods by which extraterrestrial samples are returned to Earth. In the majority of missions there will also be a requirement to document spacecraft flyby operations, impact potential, and the location of landings or impact points of spacecraft on planetary surfaces or other bodies. The nature and applicability of mission constraints required by this policy will be promulgated in subordinate NASA Management Directives.

NHB 8028.12A was released effective in February, 1976. NHB 8020.12A cancelled and replaced 8020.12 and basically revised its content by placing planetary missions in various classes of missions; and it outlined the planning, review, documentation, and schedule for the various classes of missions. While NHB 8020.12A deleted some specific requirements, it does reference the “Parameter Specification Sheets” where detailed information/requirements can be obtained.

4.3 TASK SUMMARY

At the present time, then, NHB 8020.12A and NMI 8020.7A are the two active NASA documents related to planetary protection policy and requirements, and they afford a wide basis of implementation. These documents provide for considerable flexibility in satisfying requirements for the solar system, which has wide and varying planetary protection requirements. Since this evaluation is only concerned with future missions to Mars, it is felt that requirements have been reduced too much. Missions to Mars should require sterilization implementation to the same level imposed on the Viking program. Also it is felt that the back contamination issue has not been appropriately addressed. As stated in Section 2, early research was undertaken to not only define planetary protection requirements but also develop the methodology necessary to satisfy these requirements. Little is being done at present to maintain an appropriate level of up-to-date expertise in respect to appropriate planetary protection disciplines or technologies, and this weakness could have a significant impact on projects. Recovery may be quite difficult, time consuming, and costly for the kinds of missions now being planned; and the longer such work is delayed the greater the impact is likely to be.

5.0 TASK 4 (2.4 of SOW)

The objective of this response to Task 2.4 of NASW-4355 is to outline the problems, challenges, and major decision criteria related to Viking PP and organic contamination control, and to do so in terms of how it affected the design selection for the Viking system elements as well as the mission sequence. This report will draw on the experience of project personnel who were directly associated with these issues and events.

5.1 INTRODUCTION: PERCEPTION

Over the course of the Viking program, beginning with the Voyager-Mars concept studied during the mid-1960's and concluding with the launch of two Viking flight spacecraft in August and September of 1975, the planetary protection (PP) issue evolved through a series of perceptions. At the very earliest stages, for example, PP was viewed with great concern. Its impact had been strongly intensified in response to the requirement imposed to protect the integrity of the exobiology investigations, which was to be generally resolved for the lander spacecraft components through system-wide sterilization. Because intense decontamination and Sterilization had never been undertaken with large spacecraft to the extent of the requirement specified for the Viking landers, the ways in which it could be done were not well understood, However, the anticipated problems were an extremely visible and technically overwhelming factor to be reckoned with, particularly with respect to the most probable method--dry-heat sterilization. But gradually, .over time and well before the Viking contract was awarded early in 1969, technical and management decisions were made which helped to bring the PP impact into a more realistic perspective.

In effect, Viking management integrated PP into the system-level management plan early enough and well enough to essentially render it invisible. It became an environmental specification an a par with those like vibration and solar vacuum and was dealt with in much the same way. In recalling the very earliest stages of thought on these issues, Jim Martin said 'a planetary quarantine [protection] requirement tends to extend into almost every phase of a mission, such that it is a major overriding kind of requirement that needs to be understood up front. We [Viking Project] recognized the requirement at the time, though we didn't recognize in the beginning, probably, the magnitude of the activity that would be required.' PP requirements eventually became so well embedded in other technical requirements, in fact, that it is now very difficult to identify PP activity in technical detail. Jim Martin credits the early system-level implementation not only with the success of the PP effort itself but with providing much of the impetus associated with the development of what was then a unique set of plans for qualifying, acquiring, and controlling materials and parts for the program. In this way, the PP requirements were mixed and blended with other technology requirements and translated into technical specifications throughout the program without special distinction and in a manner that was firm and reliable.

Management mechanisms needed to assure that the PP requirement was met were developed in a similar manner, rarely recognizing PP as a specific, isolated requirement but instead addressing it as one of many technical requirements in association with other program functions or tasks. For example, the procurement of materials and parts was based on specifications that included requirements for the verification of heat compatibility. While the heat-compatibility specification was but one of many, it was such a demanding specification that it was often the determining factor for qualifying a material or part for consideration. That is, because the sterilization procedure involved the entire spacecraft and no part or component could be exempted from that procedure, there was no reason to consider a part or material that could not tolerate the specified heat environment. While management authorities do not directly credit PP criteria with the outstanding success of the materials/parts control effort, they do admit that such an effort may not have been given the emphasis it received, or enjoyed the success that it did, had it not been for the heat-compatibility issue and the concern it created. Thermal analysis was, from the very start, a "must" capability for the majority of suppliers and subcontractors associated with the Viking Project.

5.2 PROGRAM DEVELOPMENT

PP considerations for launch and interplanetary flight fall into three applications: (1) launch and injection, (2) interplanetary flight, and (3) planetary encounter. Trajectory biasing and "recontamination of sterile hardware" considerations must be applied to all three cases, exposure to the space environment applies to the second and third cases, and the third must also account for orbital life and entry heating.

One of the first problems a program like Viking has to deal with is that of understanding the extent of its contamination problem in order to take satisfactory steps to resolve it. In the early 196O's, there was very little expertise in this area. As Dr. Gerald Soffen, former Viking Project Scientist, explains, "One of the valuable things that came out of the Viking PQ issue in the first place is that the planetary quarantine [protection] requirement forced us to learn a whole new technology associated with a very special aspect of bacteriology; the very process of being able to take swabs and assay organisms on a spacecraft surface, for example, was in itself a whole new technology." The organisms (spores) likely to be a problem with respect to PP requirements are, as one might expect, extremely difficult to assay, much less confirm as destroyed by any decontamination process utilized: Once again Jerry Soffen explains, "The problem tends to become one of statistical analysis, in that one contaminant is as bad as many; the effort then was to get the sterilization survival probability down to the absolute minimum. Research dealt with population death curves for organisms exposed to sterilization procedures, and the problem was how do you know when the last organism is dead. The fact is you can't."

An extremely important body of microbiological assay and decontamination research was performed both prior to the origin of the Viking program and while the lander elements were being developed. This work determined the probable bioload for lander and surface-impacting vehicles as well as the contamination potential of that bioload, and it also determined the best methods for decontaminating spacecraft subsystems and instruments to ensure that they would satisfy PP policy. Indeed, the Project required and utilized the end product of this work in many aspects of its systems and mission design as well as in determining the extent of sterilization that would be required. An extremely important product of part of this work, in fact, was the decision to use whole-system, dry-heat sterilization for ,Viking after considering a variety of gas, heated-gas, and radiation modes. This work is well summarized through the Viking experience in NASA SP-5105, Advances in Sterilization and Decontamination (a Technology Utilization Survey), prepared under NASA Contract NASI-14209 by The Bionetics Corporation, Hampton, Virginia, 1978. It should be noted, however, that the Viking summary it contains is extremely brief and superficial, and it does not contain technical information or specifications associated with the qualification, test, and Sterilization procedures.

Much of the bioassay and decontamination study work was originally conducted in NASA/California Institute of Technology facilities at the Jet Propulsion Laboratory (JPL) in Pasadena, California, and the Viking bioassay work was conducted later at the NASA Kennedy Space Center in Florida. Dr. Joseph A. Stern, President of The Bionetics Corporation in Hampton, Virginia, participated in nearly all aspects of this work. Noting the requirement imposed on the Viking lander systems, as a result of the Viking biology experiments, the chance of sterilization survival for an organism could be no greater than one chance in a million ($1x10^{-6}$). He points out that the biology requirement exceeded the COSPAR baseline requirement for PP. In that sense, then, the PP requirement established for the protection of the planet from contamination was exceeded by the Project's need to protect the spacecraft from itself. It should perhaps be noted that neither of these probabilities represents absolute sterilization (zero bioload) for Viking and that the term sterilization should not be construed to imply a zero-bioload contamination condition for a spacecraft, its components and instruments, or its parts.

Dr. Stern recalls that some of the most interesting problems were undertaken at JPL, most of it during the precursory period prior to the Viking proposal effort. It was during this period that a number of the methodologies proposed for sterilization were researched very seriously for the first time, although this work was as much a facility-development effort as one of determining the best course to follow for sterilization. Chambers were built to conduct both heat and ethylene oxide (-0) investigations, for example, but it was found that FTO was so toxic and hazardous to work with that most of the effort soon concentrated on identifying problems and solutions associated with dry-heat sterilization. Other types of sterilization were also evaluated, including ionizing radiation (such as X-rays and gamma rays) and thermoradiation (the latter in combination with heat sterilization).

He feels that the integrity of the results is highly reliable because we had to "convince the engineering and quasi-scientific community of the logarithmic relationship between numbers of organisms and their temperature and time, and that there is no such thing as an absolute death of a population. We achieved that and it is still a standard. Basic concepts that came out of the work were very well founded.' As stated in NHB 8020.12, 'Calculations involving the death of bacteria shall be based on the logarithmic death rate model. That is, for a population of bacteria subjected to a lethal condition, it shall be assumed that the percentage of cells dying per unit of time is constant.

The basic contamination equation for an entry body is: PCIE = n Ps4 P, P,; wherein: PC,, is the Probability of Contamination given entry, n is the number of viable organisms on the body at the time of entry, P,, is the probability that 2 given organism survives atmospheric entry heating, P, is the probability that a given organism is released in a region of biological interest in the atmosphere, and PG is the Probability of Growth. Probability of Growth is one of the key issues in establishing the requirements for sterilization and then implementing them. Once that has been learned, it becomes possible to examine available options about how contamination of a planet will be prevented. Alan Hoffman at JPL also recalls that dry-heat sterilization was strongly suggested by the studies of different modes of Sterilization that could be used. ETO, which was very hazardous to work with, proved to be essentially a surface sterilizer and was potentially damaging to certain kinds of materials, but dry heat could, given sufficient time to allow the coldest points within a spacecraft to achieve sterilization temperatures, essentially sterilize an entire spacecraft.

5.2.1 Mission Events and Spacecraft Systems Associated with PP Methodology

Having established very early that the spacecraft would be sterilized, and then that the method would be heat sterilization, it was clear from the very beginning what had to be done to design, build, and fly the Viking mission spacecraft. The sterilization requirement and the method selected to accomplish it immediately affected spacecraft design by adding a unique set of components and recontamination-prevention modes to the spacecraft that would not have been necessary if spacecraft-level sterilization were not an issue--the bioshield, a post-sterilization biocontamination barrier. As illustrated in Figure 5.1, the Viking Lander Capsule (VLC) included the lander itself, which was stowed and contained within the entry/descent (aeroshell) capsule, all of which was then sealed inside the bioshield.

The bioshield was a unique feature of the Viking spacecraft, and it reflected the must visible, direct influence of the PP and contamination control requirements. The bioshield was inflated with sterile, dry nitrogen gas to a modest positive pressure during terminal sterilization, and its positive pressure was then maintained to serve as a safeguard against recontamination. The pressure could be supplemented following sterilization, if necessary, and a venting system managed over-pressurization as external pressure decreased during launch ascent. To serve its function effectively, the bioshield cap had to be sealed against the rim of its base to retain the pressure, but with a seal that could be broken once the flight spacecraft was safely in space. Analyses indicated that, once in space, there no longer was a reasonable probability for recontamination of the lander capsule, and the bioshield cap was jettisoned as shown in Figure 5.2 (top left) following launch.

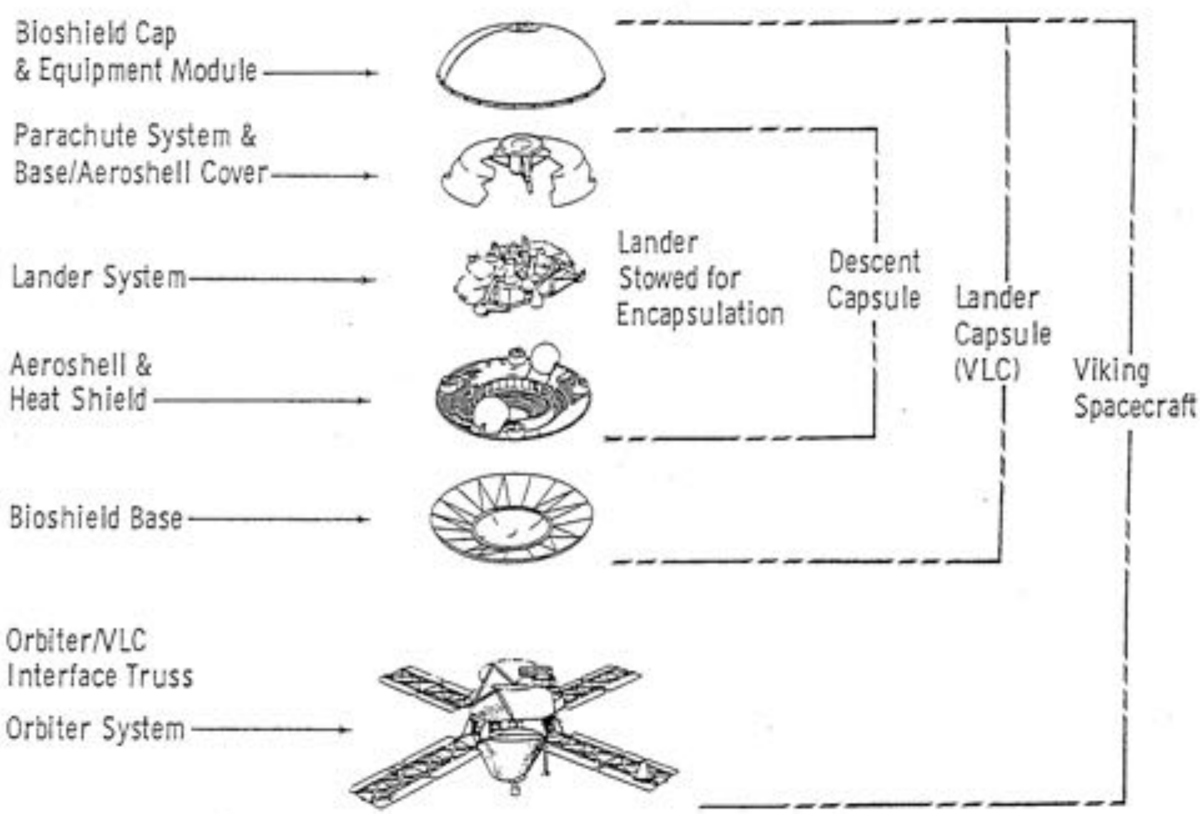

Figure 5.1 - Exploded View: Major Elements of Viking Lander Capsule

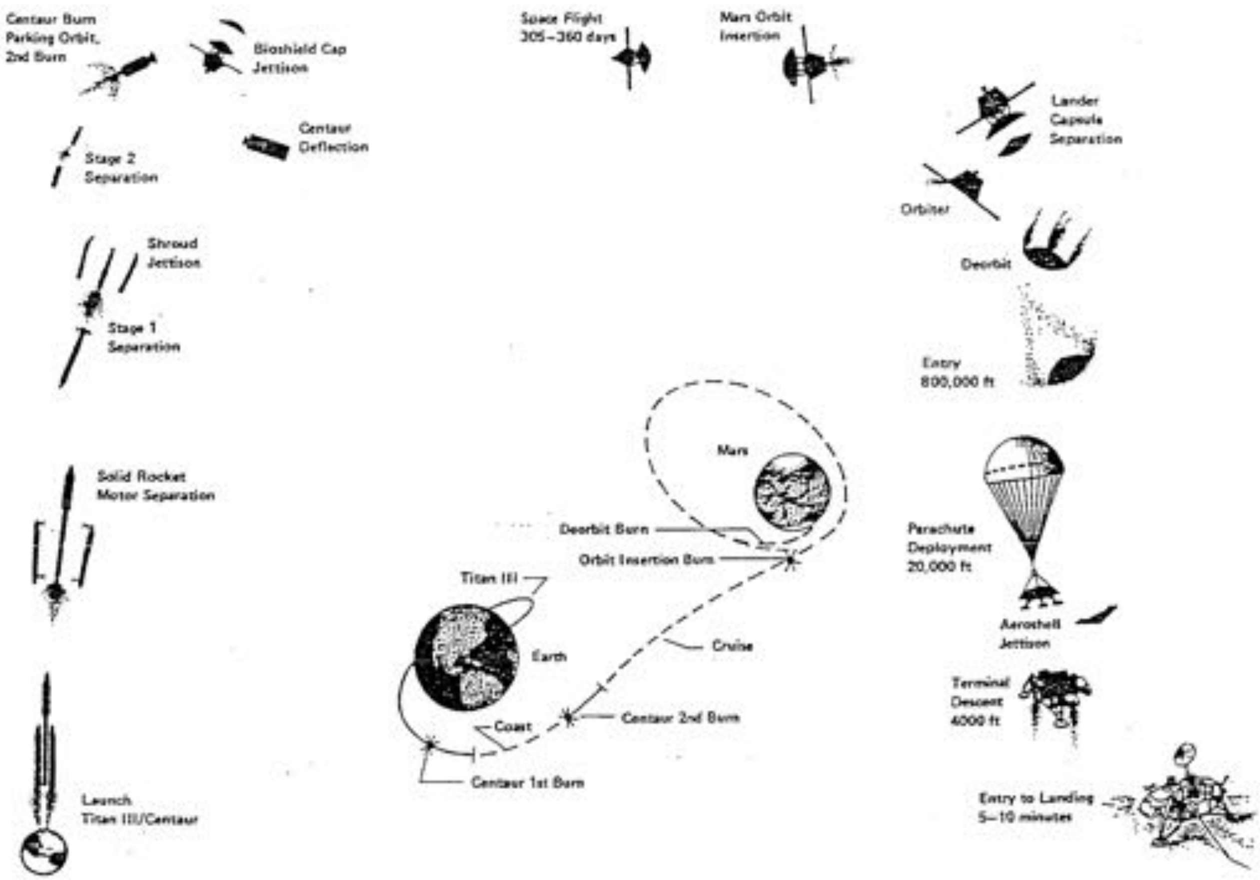

Figure 5.2 - Viking Mission Sequence Depicting Launch, Flight, and Mars Orbital Events

The base section of the bioshield, which was attached to the orbiter on a truss structure, could be jettisoned anytime after separation of the entry/descent capsule in Mars orbit. While having the bioshield base in place was not a problem for the orbiter, the base was large enough and positioned such that it tended to put some modest limits on the viewing perspective afforded the orbiter's science scan platform. The jolt experienced by Viking Orbiter 1 (VO-I) when its bioshield base was jettisoned was severe, and the flight team chose not to risk separating the VO-2 bioshield base until very late in its mission; it was successfully jettisoned without consequence.

Although the Centaur vehicle was separated from the flight spacecraft once it had provided the boost needed to inject the spacecraft into their trans-Mars trajectories, PP policy required that its trajectory be sufficiently deflected to ensure that it would not impact Mars. Similarly, because the Viking orbiters were not sterilized and did not satisfy PP specifications for landing or impact on Mars, the flight trajectories of the Viking spacecraft were designed to miss Mars by a small but acceptable margin, thereby avoiding the possibility for impact should there be a failure of an orbiter's propulsion system. A series of mid-course corrections helped to ensure flight spacecraft approach targeting for their final Mars-orbit-insertion (MOI) propulsive maneuvers.

5.2.2 Development Issues Associated with Viking PP

One must understand the impact associated with whole-system terminal sterilization to appreciate how crucial it was to develop components, instruments, and subsystems that could survive that procedure reliably and with absolute integrity. Because each VLC was sealed prior to terminal sterilization to maintain the integrity of the sterilization procedure prior to launch, a system component failure during sterilization would require opening the spacecraft to undertake repair or replacement and would automatically negate the sterilization procedure, forcing a complete recycle. Moreover, little margin was allowed in the launch schedule for a recycle, so it would then have been very difficult to reprocess the VLC in time to make its launch window.

Clearly, then, the best solution to this problem is to provide as much margin as possible with respect to the terminal sterilization procedure. What one needs is a spacecraft that is so heat-tolerant in the first place that the terminal sterilization procedure itself represents an easy environment for it to survive--hence, the importance of making the acceptance and qualification specifications sufficiently severe enough, and imposing them early enough, to be certain that terminal sterilization would not be a problem.

This kind of-environment reliability and assurance cannot be achieved through ad-hoc trouble- shooting 'on a problem-by-problem basis. It must be addressed through a systems-level implementation of specifications from the very beginning. Just as the bioshield aspect of the spacecraft and mission sequence had to be designed in as an integral system, rather than simply incorporated as an add-on, it was also necessary to achieve the heat-tolerance integrity required for sterilization the same way by incorporating appropriate systems-level thermal environment specifications, No material, piece-part, or fabrication process was accepted that could not withstand the environmental specifications established for spacecraft systems; and heat was one of those specification-defined environments. Moreover, because the materials and parts to be used were acquired and maintained in program inventories (mandatory parts and materials lists), they were tested extensively to ensure both their integrity and their uniformity.

As John Goodlette explained, many relatively common non-metallic materials used in a variety of electronic components, e.g., circuit boards and certain kinds of discrete parts, simply would not stand up to the heat environment. Adhesives, lubricants, and rubber-like parts (like O-rings, gaskets, or other kinds of seals) were a serious problem as well, some of them capable of outgassing organic contaminants; and numerous new materials were required to replace those that could not qualify. So the qualification of materials and parts was a difficult process. One of the principal lessons learned, admonished by Israel Taback, was "if you change processes or materials, watch out for the consequences."

Some of the major components most seriously affected by these problems included the batteries, gyroscopes, and tape recorders. These component development issues are discussed in Section 2.0. Because so any changes were implied and ultimately required to satisfy the heat requirement specifications, it was clear that a significant test program would be necessary in association with the qualification process much earlier than would be possible for the complete spacecraft. Because the program inventoried its required parts for mandatory use, automated test programs were established to handle the flow volume of these parts and materials and to assure their compliance with specifications. The test programs became very important elements of the program sequence, with respect to schedule and cost performance, in addition to serving as the principal mechanisms for assuring an efficient and reliable way to qualify parts, materials, and components with repetitive uniformity.

5.3 TASK SUMMARY

In terms of relating PP and contamination control issues to the program/mission sequence, it seems clear that there is a need to identify and implement the appropriate requirements as early as possible in the program schedule. The program schedule for such a complex spacecraft system, as suggested by the sample Viking schedule in Figure 5.3, is extremely full and, therefore, vulnerable to perturbations as problems evolve. The implementation itself should be a systems-level process, with PP translated into technical specifications for environmental qualification just like other environments specified for spacecraft parts and components. This is a crucial process, according to Walt Lowrie, as he recalled that subcontractors often didn't understand the problem--" ... we had to control it very carefully .... We had to insist on and get approved parts and materials, and this experience illustrates why these kinds of things need to be established and understood up front." He adds in reflection, "We did the parts and the materials management job very well, although we probably could have put more emphasis on systems engineering earlier than we did."

In conclusion, the Viking experience with PP, particularly in terms of sterilization and heat compatibility, suggests that it surfaces as a matrix of requirements that affects the Project at every level throughout the program schedule. It mandates certain technology design requirements and makes technical specifications necessary, which are then applied to the acquisition and fabrication of hardware; and it is applicable to launch and flight operations in terms of how mission parameters imposed on certain launch vehicle and non-impact/landing spacecraft systems are defined. It is clear that these issues must be understood at a very early point in the development of a program plan, as it was for Viking. It can also be seen that technical clarity, with respect to the appropriate specifications, is absolutely necessary across the program at the very start and that strong management and a comprehensive test program are vital to the process. And, finally, oversight for PP policy is necessary at the systems level to ensure compliance once the policy requirements have been translated and absorbed into hardware specifications.

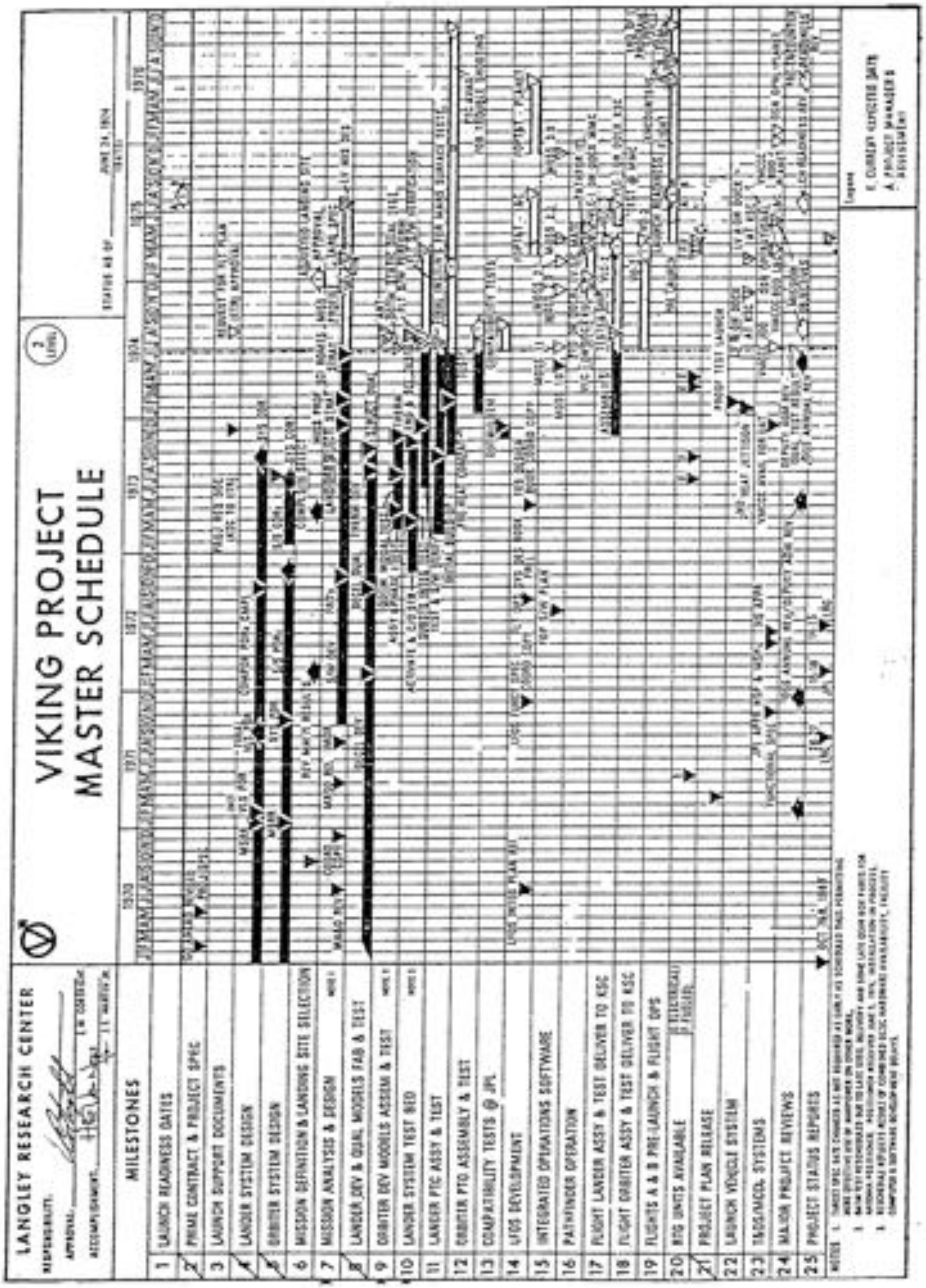

Figure 5.3 - Sample Viking Program Schedule (as of Mid-1974 Prior to Lander Shipments to Kennedy Space Center)

6.0 TASK 5 (2.5 of SOW)

This section is a compilation of discussion commentary and other information pertinent to Task 2.5 of NASW-4355. It will provide an overview of the interactive influences of PP policy and the requirements imposed by the Viking exobiology investigation, the biology and organic molecular analysis instruments. Its content will include a review of how the Viking biology and organic investigations affected the overall mission in terms of their own contamination control requirements.

6.1 INTRODUCTION: INFLUENCE OF LIFE SCIENCE/ORGANIC INVESTIGATIONS

6.1.1 The Spacecraft

It has been more than twenty years since NASA started down the path that would turn its concept for the Viking spacecraft systems into a reality, and even now the goals it established for the lander systems that ultimately set foot on the surface of Mars would seem incredibly difficult .to achieve in light of the required compactness and scientific capability. At the time the challenge was undertaken to design and build the system elements of the Viking Lander Capsule (VLC) for two flight spacecraft, modern miniature electronic chip technologies were still an evolving technology; and thermally stable, light-weight, non-metallic fabrication materials were not in widespread use on existing designs. One cannot help but be in awe that such spacecraft systems could even be developed during that period, much less perform their tasks with the remarkable precision and success the Viking Project achieved during Mars operations.

The problems confronting the design of these systems were, in a word, astronomical. While the Viking landers did reflect the design and scientific aspirations conceived for the precursory Voyager-Mars program, the deletion of the costly Saturn launch vehicle in favor of the Titan-Centaur dictated severe constraints on spacecraft weight and size. Illustrated in Figure 6.1 is an exploded view of the Viking spacecraft (center), as well as a depiction of the flight spacecraft atop the Centaur on the launch vehicle (left) and the launch vehicle itself (right). Coupled with the challenge of finding room for the comprehensive science payload while also providing space for other necessary subsystems like power, communication, data storage, and the lander's computer, the lander body and its surfaces represented a tight fit within the weight and dimensional constraints. As Figure 6.2 suggests, virtually every inch of space inside the body was occupied, while the top, side, and bottom plates bristled with what couldn't fit in the interior.

The landers were mounted to an aeroshell platform scrunched up tightly in a stowed configuration for both the flight to Mars and the upper-atmosphere entry phase of the landing sequence. The aeroshell, which was equipped with an ablative heat shield as well as a parachute-equipped cover that completed the full encapsulation of the lander, was itself a scientific platform. Mounted on its own structure were an upper atmosphere mass spectrometer, a retarding potential analyzer, and ambient temperature/pressure sensors. Figure 6.3 illustrates the encapsulation of the entry capsule and lander, as well as the nature of the landing sequence. And it should be noted that all of these components were designed to contact the surface of Mars and to be elements of the VLC; as such, all had to be developed to tolerate the heat-sterilization environment and meet the heat compatibility specifications imposed in response to the Viking Project PP requirement.

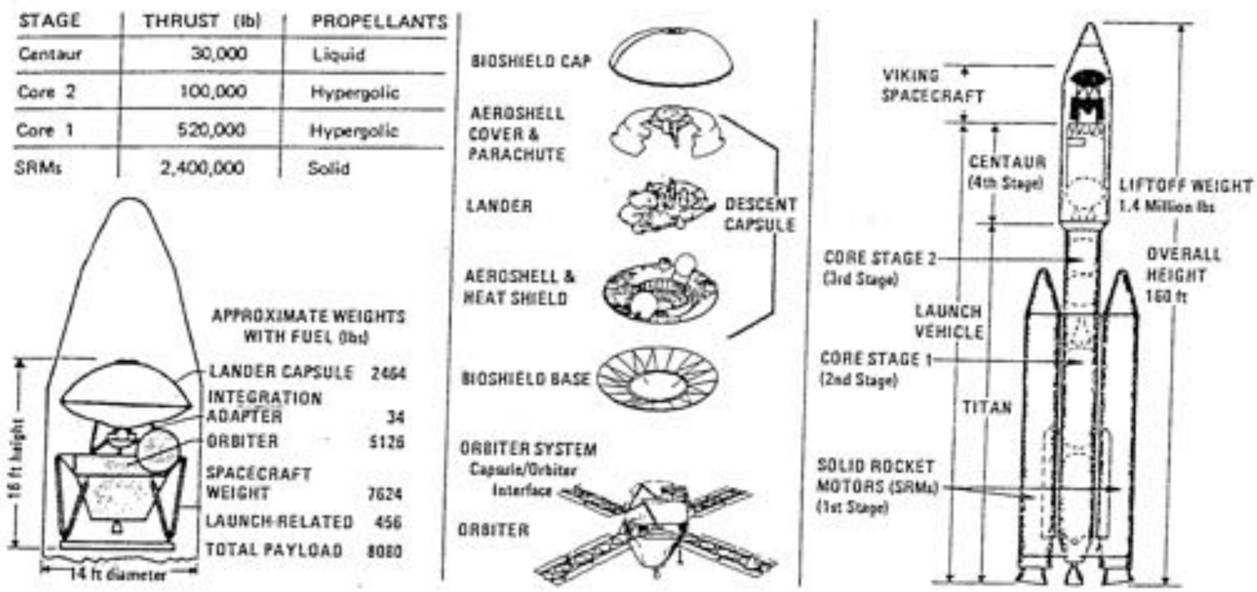

Figure 6.1 I Viking Flight Spacecraft, Exploded View, Titan IIIE/Centaur (Left to Right)

The lander body was essentially a triangular box with its corners cut off to accommodate three shock-absorbing landing legs. The six-sided box afforded a space that was only a little more than 18 inches deep within alternating sides of 43 inches and 22 inches in length. Its widest exterior dimension, including attached hardware, was under ten feet. On the surface of Mars, its top plate was expected to be about three feet above the ground while its bottom plate (with the terminal descent landing radar, TDLR, and altimeter antenna attached) was expected to be less than a foot above the ground; indeed, it is possible that the TDLR and altimeter may in fact have been much closer to the ground in light of the size and distribution of martian rocks at both landing sites.

Fully fueled, the VLC--with bioshield--weighed nearly 2500 pounds, but by the time the lander was alone on the surface, allowing for roughly 50 pounds for residual propellant, its weight was only a little more than 1300 pounds. Because the weight and size of the landers were so constrained by launch vehicle capability and mission design, every cubic inch of space and every ounce of weight had to be allocated very tightly against a total 'budget" that could not be altered, and the allocations were therefore contested emotionally throughout the design phase whenever development problems

suggested that solutions might more easily be achieved for a given component or instrument with only slight increases in allocated weight and sire. Rarely could such compromises be made, and, when they were, the changes often amounted to fractions of an inch and could be weighed in grams. This points out the significance of having firm/well defined PP requirements early in the life of the project or, as an extreme, weight problems could be resolved by the elimination of the bioshield.

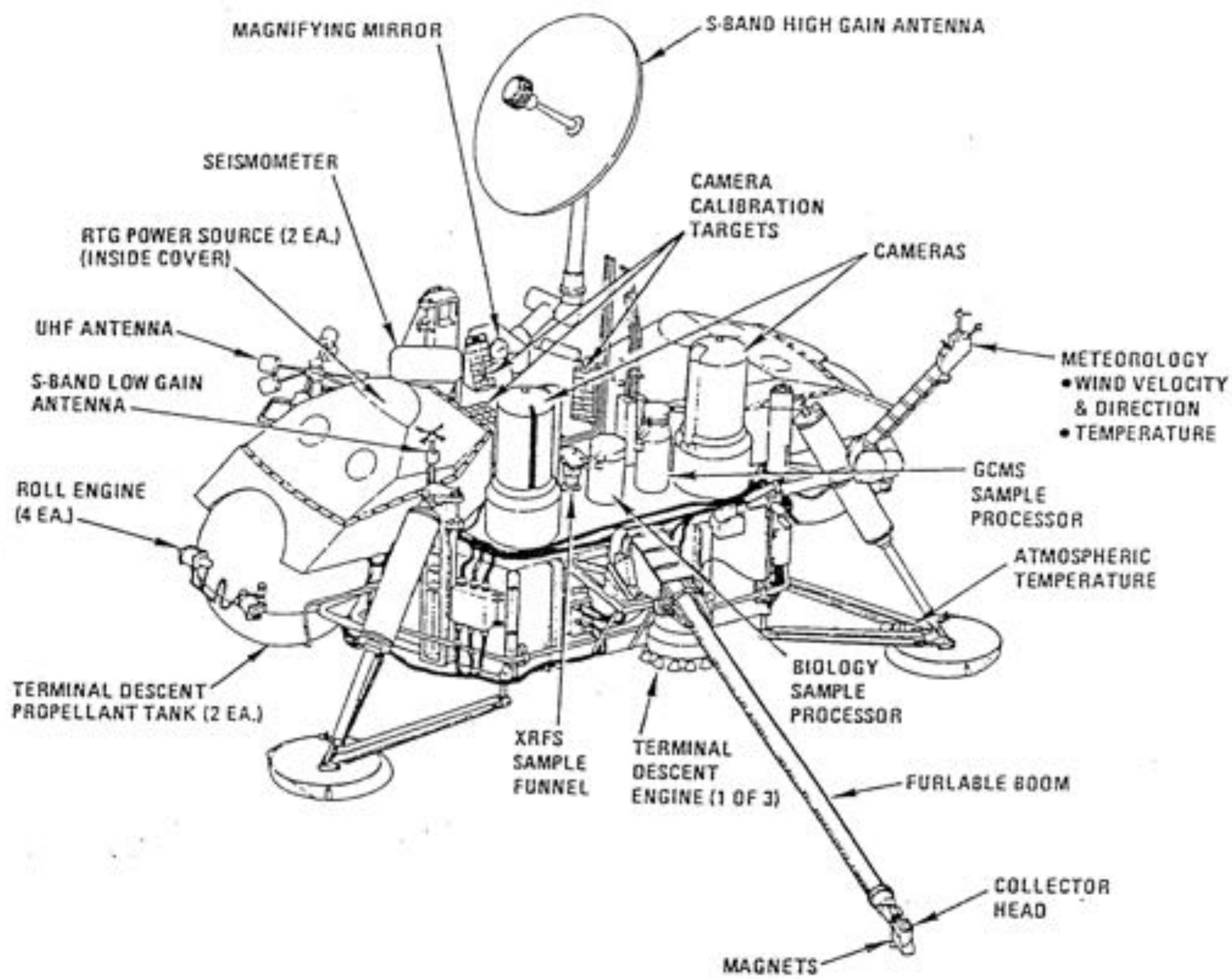

Figure 6.2a - Lander Equipment Arrangement

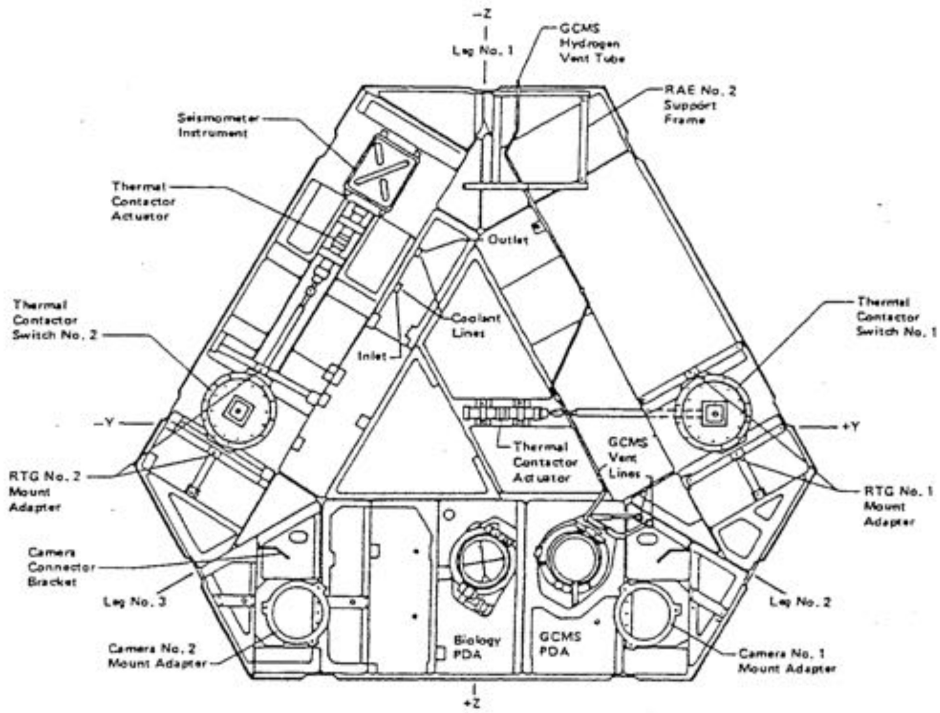

Figure 6.2b - Lander Equipment Plate Component Arrangement (Top View)

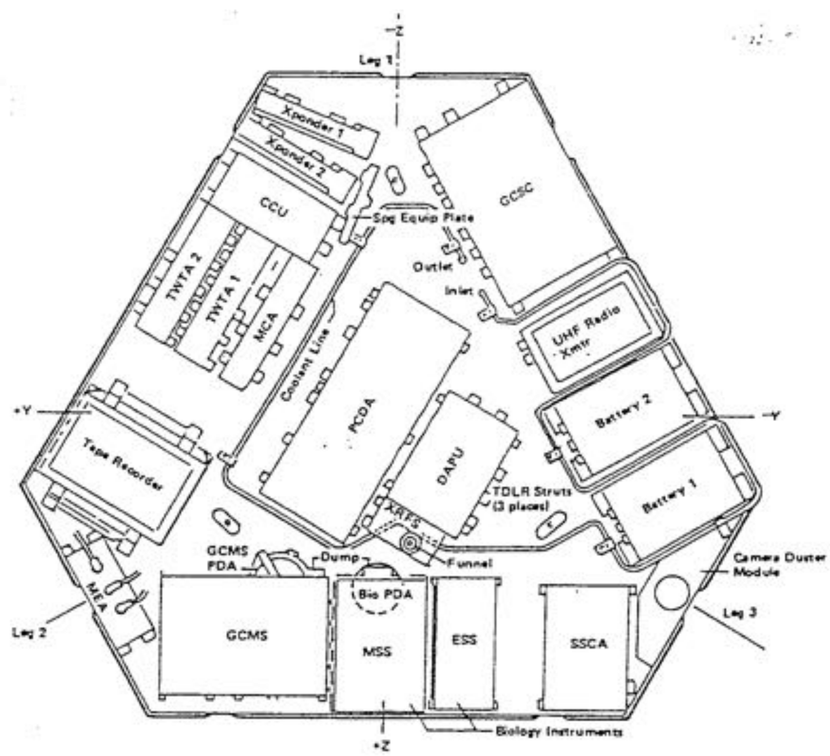

Figure 6.2~ - Lander Equipment Place Component Arrangement (Bottom View)

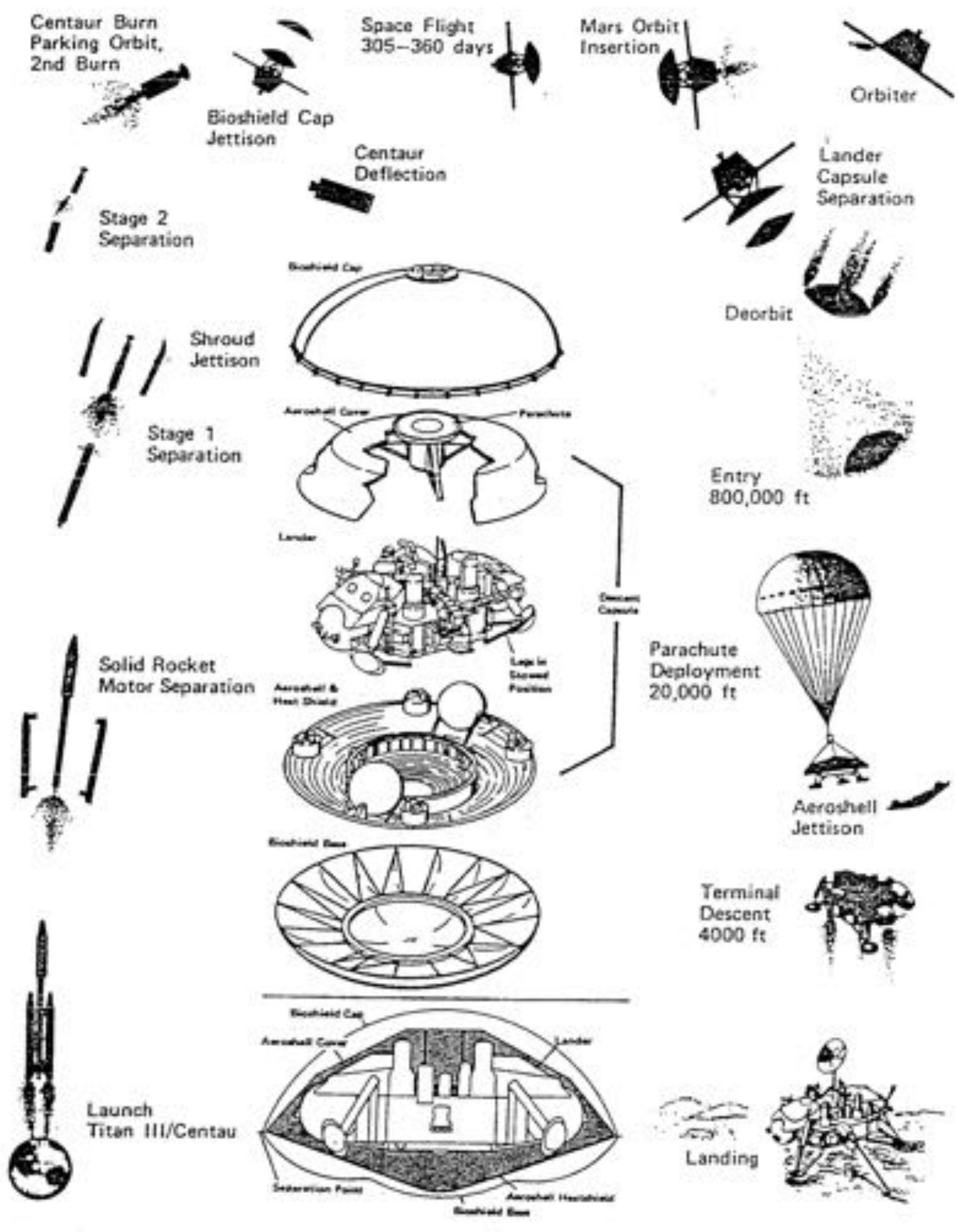

Figure 6.3 - Encapsulation of Entry Capsule and Lander

6.1.2 Exobiology Science: Instrument Design Characteristics

This design environment, then, served as the backdrop for the development of the exobiology instruments the Viking Lander Biology instrument (VLBI) and the organic molecular analysis instrument-a Gas Chromatograph Mass Spectrometer (GCMS). The VLBI, illustrated- in Figure 6.4, contained three distinctly different experiments designed to search for evidence of living organisms. In its final configuration, this miniaturized biology laboratory weighed only 33 pounds, had a volume of just under 1,67Q cubic inches, and fitted into a box that varied dimensionally only slightly from that of one cubic foot. The second of these instruments, the GCMS illustrated in Figure 6.5, was similarly a first-time development effort and also required considerable miniaturization, It was designed to perform two investigations: the first, to analyze atmospheric samples using the mass spectrometer alone and, the second, to look for organic compounds in the soil using both the GC and the MS. The latter was accomplished by heating soil samples through a series of temperatures so that vapors of differing organic compounds were driven off for absorption in the gas chromatograph column. The column itself was then heated to drive off specific family groups of organic molecules which were then drawn into the mass spectrometer for ionization and identification. The GCMS was allocated a weight of 41.4 pounds, had a volume of nearly 1,620 cubic inches, and fitted into a box I01/2W x 14H x 11 L (inches).

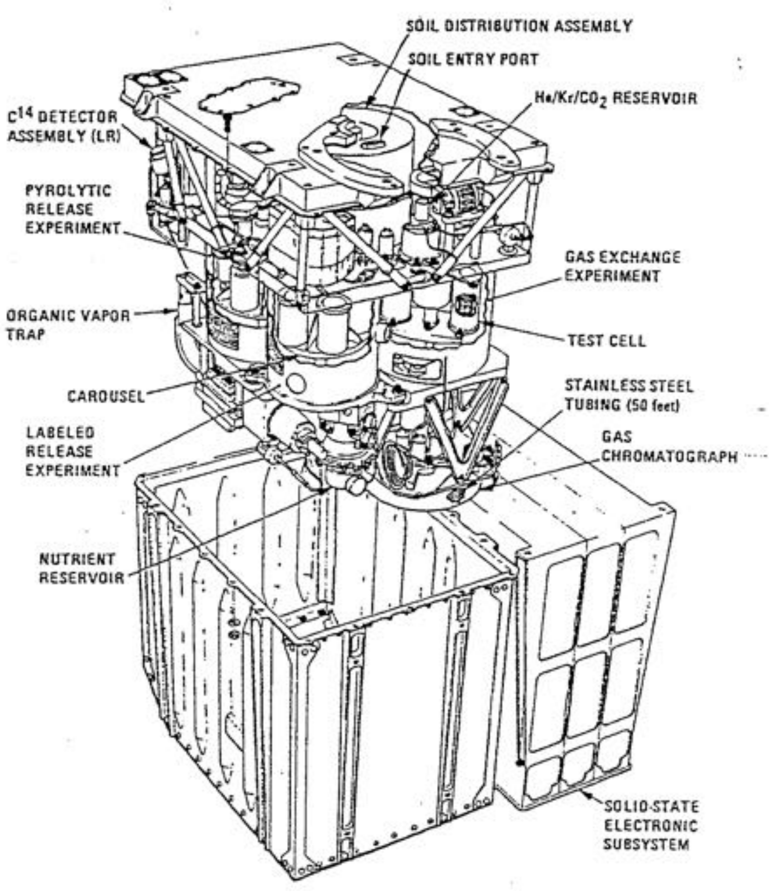

Figure 6.4 - Viking Lander Biology Instrument (VLBI)

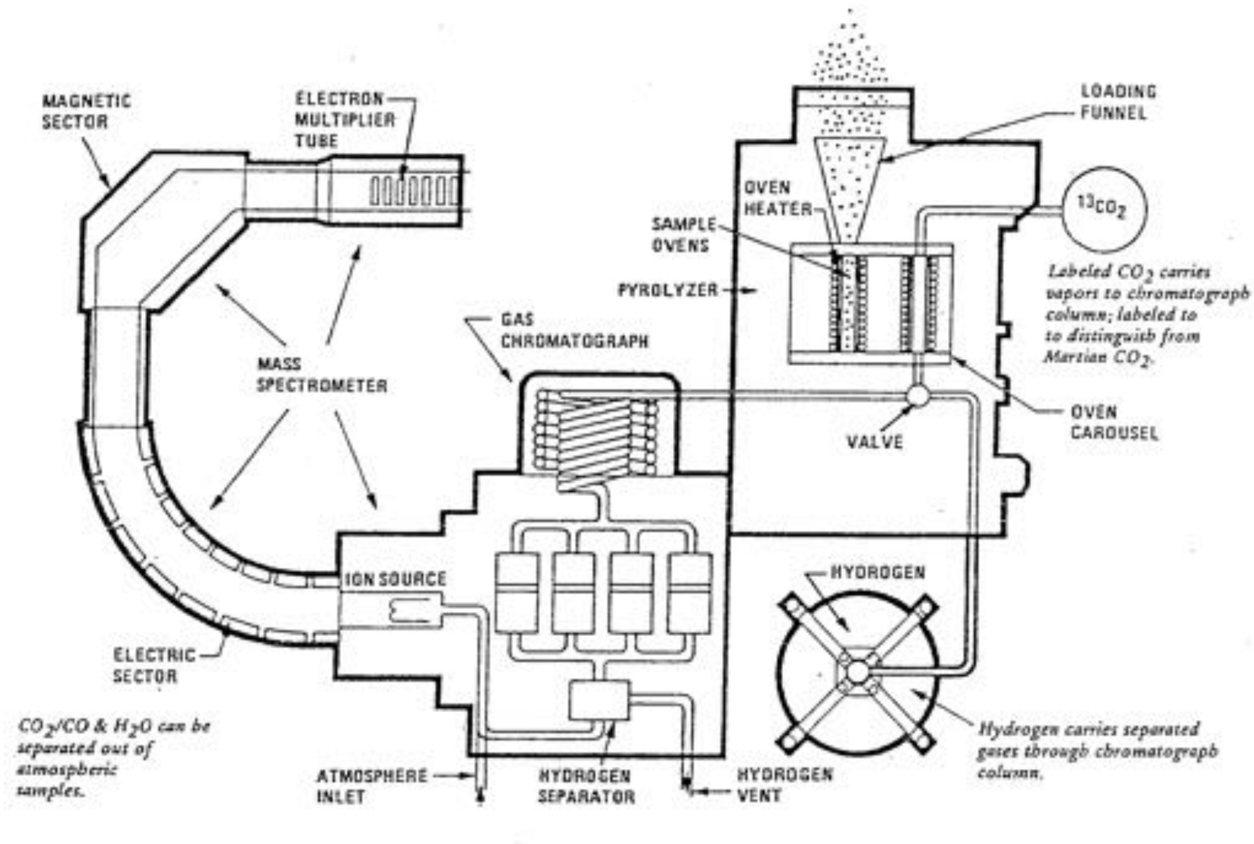

Figure 6.5 - Gas Chromatograph Mass Spectrometer (GCMS)

The two exobiology instruments were mounted next to each other inside the lander body and directly under sample processor/distributors (PDAs) dedicated to each. From the front of the lander, the GCMS PDA is at far right next to Camera 1, and the shorter VLBI PDA is just to its left. The box-like funnel distributor left of the biology PDA dropped samples into a X-ray Fluorescent Spectrometer (XRFS) for inorganic chemical analysis. In the line illustration of the lander (Figure 6.2), the VLBI and GCMS PDA lids are still closed and sealed against possible contamination of their sample paths. Another important link in the sample path, the surface sampler itself, is illustrated with its boom extended. It was designed to extend and retract much like a tape measure and to scoop and trap sail samples in its jaw, During flight, however, the sample collector boom was fully retracted and turned inward, its jaw protected from contamination by a sealed shroud; the shroud was not jettisoned until the lander was on the martian surface (both could be seen later in pictures imaged by their respective lander's cameras). Because the XRFS was designed to look only for inorganic chemistry, microbial and organic contamination were of no concern and it did not nave to be sealed; however, like all other instruments, it had to be fully heat-qualified to ensure that it could tolerate terminal sterilization.

6.2 CONTAMINATION CONSTRAINTS

6.2.1 Viking Lander Biology Instrument

While COSPAR concerns expressed in the form of NASA policy on PP used the one-chance- in-a-thousand ($1x10^{-3}$ P_C) constraint as its guideline for the protection of a planet from terrestrial microbial contamination, more rigorous constraints could be established for specific missions like Viking in which recontamination posed stronger concerns associated with the spacecraft itself. The VLBI was an extremely sensitive instrument. As Dr. Harold Klein, biology team leader, described it, since "we had instruments capable of detecting-" principal at least-a single microbial organism, given the right environment, we did not want to have a situation in which we could be confused by getting data on a terrestrial contaminant we happened to drop into the biology instrument." For this reason, a more severe sterilization regime was imposed on the instrument and its sample path to be certain that any organisms it might detect were not of a terrestrial origin. Moreover, it was believed that the spacecraft itself had to be thoroughly sterilized to provide good assurances that samples, the sample delivery path, and the instrument itself were not likely to be recontaminated, once biological barriers were broken and the instruments began operating on Mars. According to Harold Klein, "It was necessary to have a very low noise background; that is, we had to have an extremely clean, uncontaminated system.'

To deal with this concern, the Viking Project allocated a P, of one chance in ten-thousand ($1x10^{-4}$) for pre-launch, approximately $1x10^{-5}$ for the landing hardware, and one chance in a million ($1x10^{-6}$) for the biology instrument itself. This concern for protecting the spacecraft from itself, therefore, produced a terminal sterilization cycle that exceeded the one necessary to satisfy the COSPAR requirement. The $1x10^{-6}$ requirement "didn't apply to the whole spacecraft, just to the biology experiments, but it imposed an extra requirement that the Project had to recognize as it considered how to develop and sterilize the lander system.” In practice, then, it meant that in addition to anything done to keep the spacecraft extremely clean and to sterilize it (clean room techniques, clean room assembly, terminal system-wide sterilization) other sterilization procedures for both the biology package and its sample path had to be carried out in order to decrease the Probability of Contamination to the increased level we wanted for our own investigation.

In many respects the VLBI's were built up, pretty much as other instruments were, in assembly rooms maintained at very high clean-room classifications. Moreover, they were cleaned and prepared in other ways much as biological laboratory instruments are typically prepared. And then, as the biology instruments were processed through their heat compatibility tests and approached component level testing (essentially a full Sterilization procedure that all Viking components had to undergo), biology- peculiar techniques were used to maintain the sterilization of the instrument once it had been achieved. After being mated with a dedicated sample processor distribution assembly (PDA), which was itself cleaned and sealed against recontamination prior to integration with the biology package, it was sterilized [120C (248OF) for 54 hours] and placed within a sealed bag that then served as a biological barrier against recontamination. This technique is not unlike that reflected in the use of the bioshield that enclosed the entire Viking entry/descent capsule and served to maintain the sterilized condition of the capsule following terminal sterilization at the Kennedy Space Center. Once sterilized and bagged in this manner, the biology instruments were shipped directly to Kennedy; they were not removed from their contamination protection bags and installed in the landers until the landers were ready for encapsulation and terminal sterilization. Even then, the instruments and their sample paths remained sealed against internal recontamination, and any exterior recontamination was essentially controlled during the VLC terminal dry-heat sterilization procedure.

Other things were done during the buildup of the biology experiments to help facilitate and maintain good contamination control over the instrument. While the sterilization of nutrients used in biological experiments is fairly normal (usually done under steam heat in an autoclave), extra precautions were taken in the case of the Viking experiments. The nutrients were sterilized and then stored in special sealed ampules after which the nutrient ampules were again sterilized before being installed in their respective experiments. Of course, they were sterilized again during instrument sterilization and yet again during VLC terminal sterilization. The biology PDA was treated in much the same way as the biology instrument itself. It was cleaned thoroughly as it was assembled, assembly was conducted under extremely clean conditions, and the PDA was sealed and bagged as a contamination control device prior to shipment.

Harrison Wroton, Martin Marietta's resident manager at TRW, along with Norman Horowitz and Gil Levin, agreed that sterilization to the extent necessary to ensure compliance with NASA PP policy had no significant impact on the biology instrument, primarily because the instruments' own sterilization requirement was more severe. Dr. Levin was in full agreement with the biology sterilization requirement even though it cost him an important nutrient that could not withstand the hear. Moreover, it is a fairly typical practice for heat to be employed in the sterilization of biology instruments and nutrients, so that the people involved in the development of the Viking experiments had more sterilization expertise for dealing with any problems that arose. In addition, as Dr. Horowitz pointed out, the instruments had their own heating devices which were used for several purposes (e.g., samples could be heated to 160% to prepare controls, and the PR experiment could heat its samples to 650C), such that they had to be designed to be somewhat heat tolerant-at least in part-within themselves.

While it could be said that the PP policy requirement had no impact on the biology instrument because of the fact that the instrument's own requirement was greater from a surface sterility standpoint, it may also be, as Hatch Wroton pointed out, that the biology requirement "did spill over into the PP requirement imposed on other science and spacecraft systems, perhaps increasing that requirement where it might not otherwise have been necessary. In that sense, then, the effort to decontaminate the biology instrument had a greater impact than what might be suggested when thinking only about the instrument itself .... Having the biology aboard pretty much set our requirement for sterilization."

6.2.2 Gas Chromatograph Mass Spectrometer

The problem of greatest concern in the GCMS was the possibility for organic contamination, such that cleaning procedures were particularly intense for both the instrument and its sample path. Unlike the biology instrument, the organic/molecular analysis GCMS was not the type of instrument that would normally be sterilized, and its electronics were particularly vulnerable. The GCMS on the first flight capsule produced one of the only problems associated with the Viking terminal sterilization procedure, and a later failure of the VL-2 GCMS on Mars may also be attributable to the heat qualification requirement.

Heat Qualification/Sterilization. Although sterilization isn't necessarily required of an instrument like the Viking GCMS, its parts had to meet heat acceptance specifications and the instrument itself ultimately had to be heat qualified at the component level-a procedure that essentially sterilizes any component subjected to it. And, of course, the instrument was heat sterilized again during the VLC terminal sterilization procedure, such that it had to be qualified for high levels of heat like all of the lander components and instruments. In the case of the GCMS, this heat qualification process may have had a more significant impact than it had on most other lander components.

Like the biology instrument, the GCMS was a very demanding instrument to design and develop. Unlike the biology instrument, the heat compatibility issue produced a number of critical problems. One of the few problems to be detected as a direct result of the VLC terminal sterilization procedure was discovered following the VLC-I flight capsule sterilization; "the GCMS on that lander developed a leak in the vacuum envelope. There had been no previous problems with this particular instrument during any of the heat qualification tests performed on it.# Following a review of the problem, in consideration of the launch schedule impact should a recycle be attempted to repair the cause of the leak, the Project decided to live with the leak rather than risk missing the launch window. The project did not believe the leak to be serious enough to take that risk, based on what they could determine to be its impact.

But, while the leak developed in a way that made the instrument satisfactorily functional in spite of the problem, its performance was compromised at least to the extent that it was unable to make low-level atmospheric measurements. . Fortunately, those measures could be and were successfully taken on Mars by the second lander's GCMS. As Dale Rushneak described it, "I computed what the leak rate would be and determined what its effect would be on the atmospheric analysis, because that's the one we were worried about. We weren't worried about the organic experiment because the GC was connected to it, and anything coming out of the GC would have been seen independently under a dynamic condition; we would have seen peaks instead of a steady-state leak." Based on his knowledge of the instrument and the results of flow dynamics through the instrument following sterilization, he was able to pinpoint the probable fitting failure at the source of the leak.

A second failure may in fact have been a slow developing problem associated with the heat compatibility issue as well. At about the time of conjunction (late 1976), & temperatures began to get colder and atmospheric pressure dropped with the onset of martian winter at the VL-2 site in Utopia (the northern most of the two Viking landing sites), its GCMS failed as a result of what is believed to have been a corona arc in its electronics. Fortunately, the instrument had worked flawlessly up to that point, such that its scientific mission is considered to have been a complete success, but Rushneak studied the failure in great detail in an effort to explain it. "We traced the failure to a corona discharge in the power supply of the ion pump that kept the instrument clean. I can at least postulate a pathway back to the heat sterilization process, because the connector on the ion source housing and the connector on the ion pump housing--and all of the electronics--were potted.' Potting material had been a major problem across the program because conventional compounds could not withstand the heat; it was difficult to get them to adhere to the parts. As a result, it was at first quite difficult to get through a component-level thermal cycle without having some of the parts pull loose and establish a path for corona, either through the module or where the connection was located.

Organic Contamination Control. The business of contending with organic contamination control, the most important issue for the GCMS because of its designed sensitivity to organic compounds, was intense but not particularly unique or overwhelming. The cleaning chemicals and procedures used were not new, in that most of the experience originated with the Apollo program. It evolved at White Sands where it was developed for cleaning requirements associated with handling and storing lunar samples. The cleaning procedure proceeded on the basis of the instrument's performance, such that it essentially monitored and reported on its own cleanliness with each cycle. Its sample path components--the PDA and its LPA, along with the CHSU--were cleaned at White Sands as well. The cleaning procedures for the PDA, LPA, and CHSU involved freon flushing and a hated helium purge; and all were then hardware-sealed against recontamination. In the case of the PDA, which was mounted on the LPA, a lid was provided to afford that protection until it was opened on Mars, and an ejectable shroud enclosed the CHSU until the surface sampler was activated on Mars.

A few of the procedures that had been allowable for the Apollo program were not acceptable by Viking standards because they left traces of organic contamination, but correcting such problems was no more difficult than simply being a bit more selective or careful with the cleaning compounds. It should perhaps be noted that the biology instrument was cleaned chemically as well, but not nearly to the extent that the GCMS was; the biology team depended on sterilization for its required protection and did not have to be concerned about traces of organic contamination because of their detector sensitivities.

While there was nothing used by the GCMS program with which White Sands did not already have Apollo experience, it was eventually discovered (quite late in the program) that not even the best cleaning job they could do completely eliminated every bit of residual contamination. Considerable effort was expended in consideration of certain treatments of the metals, and a few of them were implemented to reduce the residual contamination to the greatest extent possible. Even this effort, as it turned out, was not quite enough. Traces of what was probably a cleaning contaminant were ultimately detected in the GCMS instruments during their Mars operations, which was fortunate; the instruments found no martian organic compounds at all, and the contaminants provided the only proof that the instruments had worked properly. Knowing that the instruments worked properly allowed the knowledge that there were no organics in the martian soil to be considered in conjunction with biology data as a basis for developing a better understanding of the nature of Mars' surface material. Indeed, the stark absence of organic detection in the instruments on Mars affords the best verification that efforts to clean them were successful.

The GCMS carousel produced a few problems as well, the biggest one being that the ovens were difficult to clean and relatively difficult to build in the assembly process. And, once built, they were virtually impossible to clean at the instrument level. For this reason, cleaning had to be extremely thorough; if a contaminant managed to evade the cleaning process during the latter stages of assembly, it would thereafter produce the peaks representative of its own signature once sample analysis got under way on Mars. Heat sterilization entered into this problem, as well, because it was possible for a small amount of contaminant to be vaporized during sterilization and then essentially contaminate the inside of the soil handling mechanism. Once again, however, the procedures applied to resolve these problems were thorough and very successful.

6.3 TASK SUMMARY

Early in the Viking program, organic contamination was expected to be a more serious problem than it turned out to be. Organic Contamination, assuming a good assembly environment and application of appropriate care in selecting parts and materials less prone to produce such contaminants, can be cleaned with relatively conventional cleaning methods and chemicals, And, unless a severe contamination source is present in the system, nonbiological organic recontamination is less probable and more easily controlled.

Organic cleanliness and contamination control in the GCMS instrument, as well as in the sample path through which the Mars surface material passed, was an outstanding success. The success was achieved in spite of the fact that many of the procedures were implemented kier in the program when the organic contamination control issue emerged, and they were implemented in what amounted to a working environment by adapting the Apollo experience.

In terms of the influence and impact of heat sterilization, the biology and molecular analysis instruments produced contrasting perspectives. In the case of the GCMS, there is reasonably good evidence to suggest that the heat environment was not as benign as most of our interviewees suggested it was for the rest of the Viking lander system. However, it is perhaps worth noting that GCMS development was unique in a number of ways in terms of how it was managed and that its development was troubled to some extent early on as a result. With this in mind, it may be reasonable to suggest that the implied heat-related problems may not have gotten the degree of attention they required for proper resolution and that the isolated development of the GCMS may have afforded some of the problems too little visibility at a point when they needed more attention. However, it is virtually impossible to pinpoint such modest differences as a source for minor technical problems ultimately experienced in such highly complex instruments-problems which could as easily be classified as isolated and coincidental failures that had nothing at all to do with any of the faults suggested.

If the Viking experience is in fact a good case for proper management, it suggests that modest changes in emphasis can have a big impact on how well a job is done. As an example of how an unmanaged problem can turn up too late, there is the GCMS case in which one sample cell oven was lost to each GCMS flight instrument principally as a result of misinterpreted test data and a very minor flaw in the oversight responsibility for operational integrity. At face value, the loss of a single oven in each lander may be insignificant; but we will never know what the science team could have done with one additional cell at each landing site. In all fairness, however, it is appropriate to note that some of the requirements for organic contamination control came to light later than the heat compatibility issues and may have attracted technical focus away from problems that might otherwise have been resolved with greater certainty.

The most important fact to recognize is that the instruments worked-and worked well! Both of the GCMS instruments ultimately completed their primary mission requirements on Mars and performed what was expected of them. Indeed, each exceeded some of its mission requirements, providing, for example, superior atmospheric analyses by producing more and better data than expected through the application of some innovative techniques. One such product was the identification of three noble gases-neon, krypton, and xenon-using a unique enrichment process to detect trace constituents the instruments could not otherwise detect (Dr. Tobias Owen/Dale Rushneak). This success allowed the science team to determine the relative abundances of certain isotopes that afford a better understanding of the planet's history.

In the case of the biology instrument, it does appear that heat was not seen as a major problem. However, there is evidence to suggest that heat did aggravate some of the other development problems as well as the test and qualification path. As in the case of the GCMS, it is probable that the issues associated with heat qualification were so overwhelmed by the new technology required in the instrument itself that they seemed smaller and relatively invisible within the shadow of the larger problems. Unlike the GCMS case, however, this reduction of the apparent concern about heat apparently produced no major problems for development or in the operation of the experiments on Mars. The biology instruments, once fully qualified and installed on the flight landers, came through terminal sterilization and all subsequent operations with no evidence of heat degradation. Indeed, the instruments produced their best checkout performance data on Mars, and then followed that up by completing all of their required experiment cycles as planned. The experiments themselves were clearly free of any terrestrial contamination, worked at least as well and often better or more productively than anticipated, and were able to produce some extremely interesting and valuable data with respect lo our understanding of the surface material on Mars.

7.0 SUMMARY AND CONCLUSIONS

After completing the five activities required by this effort and reviewing the Summaries associated with each task, it became apparent that there is a consistent message coming from each one: It is hoped that this message is not an influence of the writers of the report. Certainly the results-of the interviews of the various scientists, managers, engineers, etc. are not biased by the writer and can serve as an objective viewpoint, although there are varying opinions in the interview section. Several conclusions can be drawn from this effort.

First, PP is an important issue and must not be taken lightly. It has the backing of the world, scientific community as represented by the Committee on Space Research. If there is disagreement in the scientific community over PP, it is with various elements of the subject matter but not with the intent of the overall requirement. The second conclusion is that NASA, in the 196O's, accepted the PP requirements and initiated policies and procedures necessary to implement these requirements on their flight projects to planets of biological interest. Research was accomplished to translate the general requirement into specific ones for projects as well as to determine acceptable approaches that projects could implement in satisfying the requirements. Third, top management within NASA (Headquarters, Field Center, and Project level) supported the implementation of the PP requirements. Top management for Viking's prime contractor also supported and implemented the details of these requirements throughout all disciplines within the Project. There was no question in anyone's mind, at any level of the Project, as to what the PP 1-equiremerrls were in their areas of responsibility, that they were to be implemented in a technically acceptable manner, and that any problems were to be brought to top management's attention so that the appropriate disciplines/resources could be brought to bare to achieve a technically acceptable resolution in a timely manner.

Regarding PP on the Viking Program, it can be said that there was a requirement supported by the scientific community; NASA performed early research to support the definitions of detailed specific requirements and approaches to satisfy these requirements; and all top management associated with the Program supported the implementation of the requirements. The results of this approach is history and was successful. This study suggests that this PP approach continue to be followed on precursor missions to Mars prior to manned missions to the planet. These precursor missions must provide the data necessary to determine if Mars is a planet of biological interest. This determination could result in extending/escalating present requirements or eliminating all PP requirements.

Program self-implementation of biology experiment self contamination restrictions is not a difficult problem with PP as the standard bearer. The Viking experience is directly applicable in this case to protecting the experiments from self-contamination. Without PP requirements, the same as Viking requirement, self-contamination could have a significant impact on the success of the mission and should be evaluated in detail early in the mission planning to determine specific requirements and assess their impact.